

Abstract

Suspended sediment concentration in meltwaters draining from Alpine glaciers vary considerably both diurnally and seasonally. In order to characterise sediment variability, sub-daily close-interval sampling measurements of suspended sediment concentrations are usually undertaken. In close-interval sampling, concentrations are assessed in small volumes of water (< 250 ml). Suspended sediment concentrations can be determined instantaneously and continuously using photoelectric sensors on volumes of ~1-2 ml meltwaters. However, according to the nature of the sediment in suspension, occasional larger particles amongst the general silt fraction contribute to the weight of sediment in a sample. Suspended sediment concentration in meltwater in the Gornera, the only melt-stream draining from Gornergletscher, Wallis, Switzerland, during the summer ablation season of 1982, were assessed using three methods, with differing sampling intervals in time, with differing volumes of meltwater. Meltwater samples of < 200 ml were collected hourly by a Manning S-4050 automatic liquid pump sampler, and filtered for gravimetric determination of sediment content. This is the original method of collection and data for all three methods was calibrated into kg/ day. This method correlates positively with discharge as the R^2 measured 0.16, and the p-value was also lower than the alpha ($p = < 0.00$) meaning the correlation is statistically significant. Photoelectric measurements were determined continuously with a Partech 740 suspended sediment monitor, and were extracted during hourly intervals. This method did not correlate with discharge because even though the R^2 is strong (0.76), the p-value is higher than the alpha, meaning correlation is not statistically significant. Large samples of 50 L were collected once a day by a large aluminium cone, with the height of the settled sediment cone being recorded. This method did not correlate with discharge because the R^2 was non-existent (0.00) and p-value was higher than the alpha ($p = < 4.23$), meaning the correlation is not statistically significant. Close interval methods proved to be most representative as they show more temporal variation, however, sediment cones show less variation due to once a day samples being collected. The Manning method proved to show most diurnal variation meaning it is most representative, other methods seem to underestimate values or seem to be limited.

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Declaration

I certify that this thesis consists of my own original work. All quotations from published and unpublished sources are acknowledged as such in the text. Material derived from other sources is also indicated.

The total number of words in the main text is 19,826 (excluding references)

Name: Richard Peters

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Date:

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Richard Peters

“It always seems impossible until it’s done.”

Nelson Mandela

1. Introduction

High mountain regions of the world contribute large quantities of runoff, derived from seasonal snow pack and glacier ice, to the headwaters of the world's major rivers, with mountainous areas seen as water towers for surrounding regions (Viviroli, 2007). Glaciers exert significant control on runoff and sediment yield from high mountain basins. Partly-glacierised basins are more complex hydrologically than non-glacierised basins, runoff responding to both thermal and precipitation inputs. Glaciers are powerful agents of erosion, contributing large amounts of fine sediment to meltwater (Gurnell *et al.*, 1996). Meltwaters flowing in conduits and cavities at the bed of a glacier interact with the products of glacial erosion which are transported from the terminus into the downstream fluvial system (Leggatt *et al.*, 2015).

Following closure under ice overburden pressure during winter, each spring the drainage system beneath an Alpine glacier becomes re-established as surface meltwaters start to penetrate to the glacier subsole. Evolution of the basal drainage network during the ablation season is influenced not only by seasonal patterns of hydro-meteorological conditions but also by the magnitude, timing and sequence of hydrological events during which large quantities of suspended sediment are evacuated by meltwater from beneath the glacier to the portal (Collins, 1990).

Subglacial erosion processes occur throughout the year but meltwater flow is restricted to the warmer months, so that sediment transport is determined by interaction between the daily and seasonal patterns of meltwater discharge and the amount of sediment available beneath the glacier (Legatt *et al.*, 2015). Suspended sediment concentrations in meltwaters therefore show both short- and long-term variations which can relate to discharge as the sediment load needs discharge for transportation so concentrations can be measured. Such variations are difficult to model and predict. The scale of variation dominates any underlying secular trends such as may arise from changing climate. Knowledge of suspended sediment loads in rivers has become increasingly important and necessary in recent years. One reason for this interest includes evaluation of sediment transport to the oceans (Walling, 1977),

however, there are several more viewpoints: assessing rates of glacial erosion, accumulation of sediment in hydropower dams and reservoirs, damage to pumps and turbines and downstream water resource management (Lawson, 1993).

Small quantities of fine sediment are continually supplied to meltwaters during the ablation season through frictional melting of the basal ice layer above flowing threads of water and from the margins of passageways which allows meltwater to move laterally onto stored basal sediment (Collins, 1990). Suspended sediment transfer in meltwaters from mountain glaciers are sensitive to changes in river flow (Stott *et al.*, 2008) as glaciers are regarded as sensitive indicators of climatic variability in high mountain regions (Oerlemans, 1994). However, during the ablation season, diurnal variations of meltwater discharge from the portals of alpine glaciers are accompanied by roughly phased but inverse fluctuations of the solute.

Subglacial water is extremely important for hydrological studies of glaciers, and also to measure suspended sediment transport in a proglacial stream. A hydrological network at the bed of a glacier must allow movement of meltwater from places with high pressure to places of low pressure where refreezing can occur and permit the transfer of large quantities of melt water closer to the glacier terminus (Loizeau and Dominik, 2000). A meltwater river's total mean area and velocity determines how much sediment it can carry, but it is difficult for a non-glaciated basin to carry considerable amounts of sediment if discharge is minimal due to an insufficient level of energy for transportation, which means concentration rates would be high (table 1).

Table 1.0: A matrix table showing how discharge rates and availability of sediment can affect suspended sediment concentration with a low- medium- high scale.

Discharge (Q)	Sediment availability	Suspended sediment concentration
High	Low	Low
	High	Medium
Medium	Low	Low
	High	Medium
Low	Low	Medium
	High	High

Table 1.0 shows a corresponding relationship between suspended sediment concentration and discharge in a meltwater river depending on sediment availability. Concentration levels depend on availability of sediment and the total volume of water available for transport. When volumes of water increase and sediment availability is relatively low, sediment concentrations will also be low. Sediment concentration will peak when discharge is low but sediment availability is high due to low energy levels. Sediment availability is an

extremely important parameter in terms of how high or low concentrations are as it determines total mass/volume of suspended sediment in a proglacial river.

1.1. Aims and Objectives

The aim of this thesis is to distinguish a relationship between suspended sediment concentration and discharge in the Gornera, which is a meltwater river located in the Swiss Alps for the ablation season of 1982. One objective to help achieve the main aim is to investigate which method of data collection for suspended sediment would be most suitable for estimating the total sediment load into the Grande Dixence hydroelectric adduction galleries (Table 1.1).

Data has been collected through numerous different methods including a Partech 740 photoelectric suspended sediment monitor which collects data automatically every two seconds on a Rustrak recorder, 50 L sediment cones that are taken manually once a day, and a Manning automatic liquid sampler which collects data automatically through a tube into numerous bottles hourly. A further objective for this investigation is to provide useful information for future reference towards hydro meteorological data collection within the Gornera region to help provide a better knowledge and understanding of data collection methods used for suspended sediment. One purpose of quantitative data analysis is for identification of any future trends that may occur during a period of extended glacial recession with such trends being extrapolated through different modelling techniques.

Table 1.1: Objectives addressing the predominant aims of this study.

	Core Scientific Objectives	Method	Reference chapter (s)
Objective 1	Assess the relationship between suspended sediment concentration and discharge from the Gornera for 1982.	Compare suspended sediment concentration data against discharge from 1982 and create correlation models.	4, 5
Objective 2	Evaluate methods of data collection appropriate for estimating total sediment transport from an Alpine glacier.	Create photoelectric sediment, sediment concentration and sediment cone models (with discharge) for the same days and compare results.	4, 5, 6
Objective 3	Determine which method of data collection is most suitable for this study (Photoelectric, Manning, Sediment Cone).	Evaluate models created in objective 2 and determine which method suits this study best.	5, 6
Objective 4	Judge which method of data collection would be best suited for future studies.	Analyse results and detect which method of data collection would be the best to use in the future.	5, 6, 7

1.2. Layout of thesis

The structure of this thesis is based on suspended sediment and discharge data used for analysis (figure 1.1). The introduction chapter gives a detailed account about suspended sediment and discharge and a brief insight into what this thesis is aiming to achieve. The Literature Review gives an insight into key parts of this thesis such as sediment flux, discharge and climate. Study area follows after literature review and this chapter shows location of gauging stations which were involved in data collection and also a digital terrain model that produces high quality maps. The section describes how this map was created and different processes that can be added to the map to enhance imagery. After the study area chapter is methods, and this chapter explains different ways of data collection and which tools and equipment were required. This chapter also explains the three main forms of data collection. The results chapter follows methods, and here, findings have been analysed to help address the main aim. The discussion follows after results, this section relates work carried out to the literature and explains findings within the data. The final chapter is a conclusion where the main aim and objectives are answered. Problems with data collection are also explained in this chapter. References are included after conclusion.

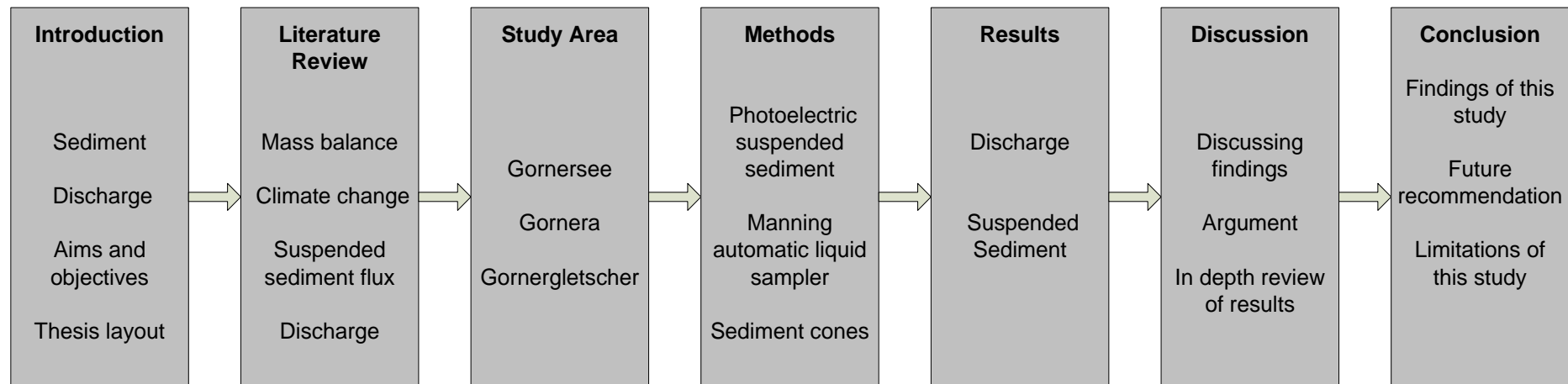


Figure 1.1: Breakdown of thesis layout created on Microsoft Visio.

2. Literature Review

This chapter presents an insight into different climatic features which affect a glacier's appearance, and how discharge and suspended sediment transport are also affected. Climate change may greatly influence discharge from glacierised catchments, with river flow varying depending on global and regional warming (Barry, 1992), as most winter and some summer precipitation will fall in solid form as snow. In high mountain areas, such as Gornergletscher, winter precipitation tends to accumulate to create a stable winter snow pack. In spring, snow starts to melt and contributes towards run-off as the transient snow line rises up basins. In partially glacierised catchments, the rising transient snowline can expose glacier ice to melt which also causes run-off to increase as the bare ice area expands until energy levels drop towards the end of the summer period.

Maximum discharge levels depend on a glacier's total area and how much precipitation there is in the winter period as the more precipitation that falls, generally there will be more ice/snow melt. Glaciers affect strongly the hydrological regime of the catchment in which they are located by storing water in winter in the form of solid precipitation, and releasing it in summer through ablation. They also alter the diurnal hydrograph during the melt season by increasing daily variability. Changes in glacier area and volume, therefore, are likely to have an impact on the water availability in such catchments, changing both its amount and timing of release (Pellicciotti *et al.*, 2010).

2.1. Mass Balance

Mass balance is crucial in terms of glacial survival as accumulation and ablation periods have to balance each other out, and if an imbalance occurs, a glacier will either retreat or advance depending on climate. There are five main factors in high mountain environments that contribute to help keep mass balance (figure 2.1). The first major factor is climate, which is an extremely important factor as this controls how the face of a glacier appears, and can determine how high or low a transient snow line can be which can affect discharge. Climate change may cause variations in both temperature and snowfall.

The accumulation period is another important parameter, which occurs during the winter months where snowfall peaks and discharge mostly freezes and turns to ice. Ablation follows accumulation, and the ablation season determines how much discharge occurs due to ice/snow melt peaking during the summer months. Mass/volume of snow and ice gained in the accumulation period and mass/volume of snow and ice lost in the ablation zone determine glacier mass balance. If the accumulation season is short and ablation season is long, a glacier will retreat because less snow/ice has been stored and snow/ice melt has increased which also means the transient snowline pushes higher up a glacier. During ablation, different glacial features such as meltwater streams and subglacial lakes can appear.

One other important parameter in figure 2.1 is discharge, as increasing discharge, generally means more melting. Snow and rain affects discharge and both inputs can occur during same time periods, however, snow mainly falls in the accumulation period whereas rain normally falls in the ablation period. Sediment transport also plays an important role in sustaining mass balance, as sediment is mainly transported through discharge flowing downstream and creating a solute/sediment flux, unless extreme weather conditions such as strong winds or earthquakes allow sediment to be transported. There tends to be more sediment transport during ablation as discharge is higher and helps to carry suspended sediment. All these parameters contribute towards mass balance, however, two key factors

in this process are accumulation and ablation as they help keep stabilities within a glacier. However, increasing global temperature is causing glaciers to retreat more than advance.

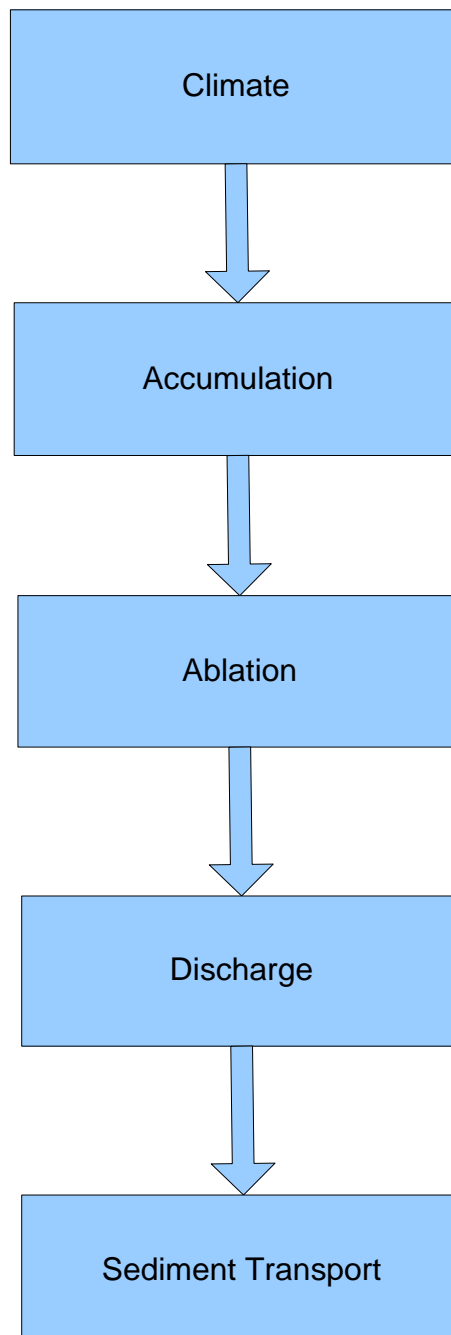


Figure 2.1: A flow chart showing different processes involved in keeping a glaciers mass balance.

In areas outside of Arctic regions, glaciers are determined seasonally by two periods of an annual glacial cycle; accumulation periods, which occur during winter periods and ablation periods, which mostly occur during summer months (Hodge *et al.*, 1998). Also, glacier mass balance is highly sensitive to regional atmospheric conditions around the glacier and to any changes that occur in that given year (Hodge *et al.*, 1998). When observing changes in climate, studies of mountain glaciers have proven to be significantly important, particularly in recent years as temperatures have increased. For the European Alps, climatic changes have been documented throughout history with observational records of local glacier mass balance (Haeberli *et al.*, 2007). These records can prove that glacier mass balance is largely affected by changes in climatic conditions of a basin.

2.2. Climate Change

Climate change is thought to have an accelerating impact on the way glaciers appear today as Earth's climate system is powered by solar radiation and approximately half of the energy from the Sun is supplied in the visible part of the electromagnetic spectrum (Barnett *et al* 2005). As the temperature of Earth has been relatively constant over many centuries, the incoming and outgoing solar energy must be similar to create mass balance (Paterson, 1994). Of the incoming solar shortwave radiation, about half is absorbed by the Earth's surface (Oerlemans, 2001).

Based on the temperature of Earth's surface the majority of outgoing energy flux is in the infrared part of the spectrum (Kiehl and Trenberth., 1997). Long-wave radiation, also referred to as infrared radiation emitted from Earth's surface is absorbed by certain atmospheric constituents—water vapour, carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and other greenhouse gases (Kiehl and Trenberth, 1997). Human interference is one of the main reasons for a changing climate (Houghton, 1996), and climate change poses risks for human and natural systems through extreme weather conditions and considerable changes of Earth's surface such as receding glaciers.

Climate change is most certainly a long-term challenge worldwide, especially in Alpine regions, but one that requires immediate action given the scale and pace in which greenhouse gas is accumulating in Earth's atmosphere (figure 2.2). In the context of climate change and receding Alpine glaciers, expansion and evolution of proglacial zones is of importance to assess implications of accelerated deglaciation and discharge modification on sediment transfer from mountain to foreland zones (Geilhausen *et al.*, 2012).

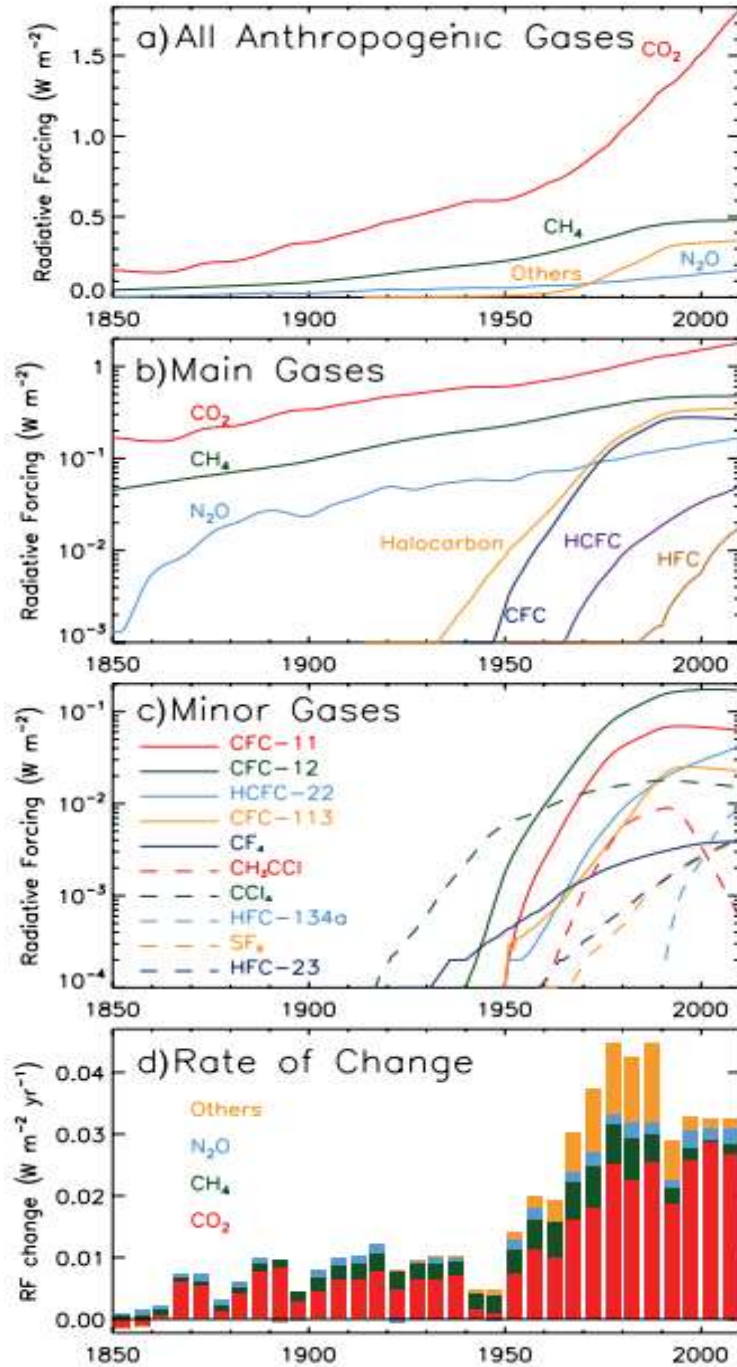


Figure 2.2: (A) Radiative forcing from the major well-mixed greenhouse gases (WMGHGs) and groups of halocarbons from 1850 to 2011, (b) as (a) but with a logarithmic scale, (c) radiative forcing from the minor WMGHGs from 1850 to 2011 (logarithmic scale). (D) Rate of change in forcing from the major WMGHGs and groups of halocarbons from 1850 to 2011 (Myhre *et al.*, 2013).

Glaciers in high mountain regions across the globe have been in a general state of recession since the Little Ice Age maximum glacier extent (1850). The process of deglaciation has accelerated since the 1980s as air temperatures have risen and precipitation levels decreased (Beniston *et al.*, 1997). When the climate change debate began in the late 1980s, estimates of the amplitude of warming according to greenhouse-gas scenarios suggested that global average temperatures could rise by 1.5– 5 °C by the end of the twenty-first century (figure 2.3). Over two decades later, with climate models that have become much more detailed, the plausible range of global atmospheric temperature increase remains essentially unchanged: 1.5– 5.8 °C according to the Intergovernmental Panel on Climate Change (Beniston, 2010).

The temperature of Earth on average has been increasing since the early 1900s to the early 2000s, and a report from the United Nations' Intergovernmental Panel on Climate Change (IPCC) estimates that the global average land and sea surface temperature has increased by 0.6 °C since the late-19th century, with most change occurring since 1976 (Hughes, 2000). Climate change is dramatically affecting glacierised parts of the World such as Gornergletscher, Swiss Alps, which has retreated 2600 m since 1865 (Holzhauser *et al.*, 2005). New analysis of proxy data for the Northern Hemisphere indicates that an increase in temperature in the 20th Century is likely to be largest of any Century during the past 1,000 years (Mann, 2006). Temperatures have carried on rising since 1975 up until after 'the pause' occurs at the start of the twenty-first Century where temperature increase has pretty much come to a halt, but this has prompted speculation that human induced global warming is no longer happening, or at least will be much smaller than predicted. Others (Seneviratne *et al.*, 2014) maintain that this is a temporary hiatus and that temperatures will again rise at rates seen previously.

One direct influence on run-off is climate, the warmer the climate the more run-off will occur. The delivery and transport of sediment through mountain rivers affects water resource infrastructure. While climate change is widely expected to produce significant changes in hydrology and stream temperature, the effects of climate change on sediment

yield have received less attention (Goode *et al.*, 2012). It is clear to see from previous studies that climate has a large effect on run-off (Beniston, 2010; Mann, 2006; Goode, 2012) but there are also external factors that can influence climate and it can be broadly compared using the concept of radiative forcing. A positive radiative forcing, such as that produced by increasing concentrations of greenhouse gases, tends to warm the surface and negative radiative forcing tends to cool the surface. Natural factors, such as changes in solar output or explosive volcanic activity, can also cause radiative forcing (Houghton *et al.*, 2001).

Various factors can contribute towards a changing climate, atmospheric and oceanic warming. Masses of snow and ice have diminished where satellite data shows that there are decreases of about 10% in the Northern Hemisphere since the late 1960s (Watson and Albritton, 2001). Warming of the climate is unequivocal and since the mid-nineteenth century, numerous notable changes are unprecedented from decades to millennia. One notable physical variation due to climate change is that mountain glaciers are retreating on all continents, and Northern Hemisphere permafrost is thawing according to the IPCC (Watson & Albritton, 2001).

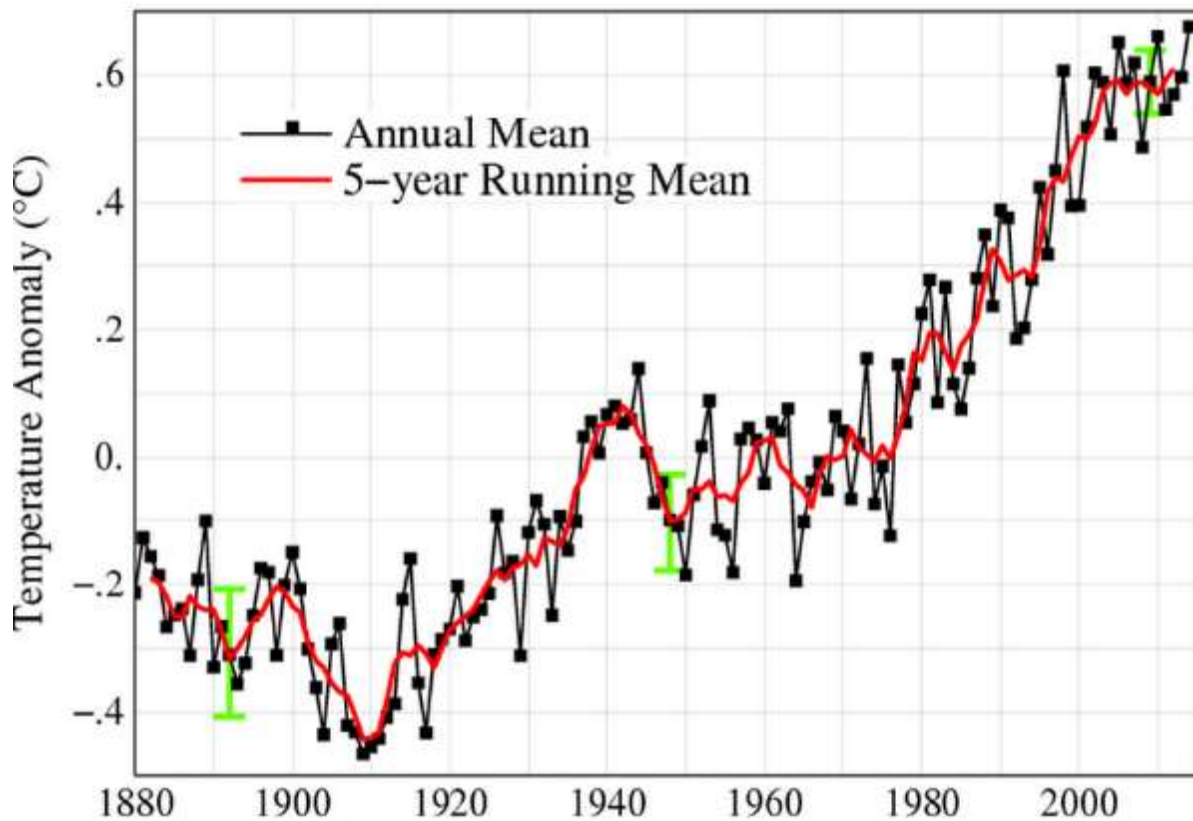


Figure 2.3: Line plot of global mean land-ocean temperature index, 1880 to present, with the base period 1951-1980. The dotted black line is the annual mean and the solid red line is the five-year mean. The green bars show uncertainty estimates (Hansen *et al.*, 2010).

With water flow increasing due to ice melt in mountainous regions, this changes the way in which suspended sediment yields appear because of a rising transient snowline more sediment will become visible. Glacial erosion produces large amounts of sediment temporarily stored in unconsolidated, loose and potentially unstable landforms, for example, moraines (Geilhausen *et al.*, 2012). However, previous studies have suggested that there is a relationship between climate change and suspended sediment concentration as Huss *et al.* (2007, p. 1930) state 'rapid shrinkage of ice volume and glacier extent took place in recent decades due to climate change'.

As ice flow/ice melt travels downstream it can attract sediment through many different ways. The high relief and the steep slopes are an obvious feature of mountain areas. The

cold climate is another factor controlling runoff and erosional processes, and the distribution of vegetation is also controlled by the prevailing climate. Above the tree line, processes of erosion are more intense than those operating below. However, mountain areas are of varying character and the conditions differ greatly from one region to another and from low to high latitudes. One of the main difficulties when attempting to generalise with respect to processes of erosion and sediment transport in mountain areas is the dominating influence of bedrock geology and the thickness and nature of the overburden.

2.3. Suspended Sediment Flux

Suspended sediment flux events in the Gornera are generally associated with, but can be independent of, increases in runoff induced by thermal conditions, rainstorms, and emptying of the Gornersee. Such increases in flow can trigger spatial instability in the drainage system beneath Gornergletscher (Collins, 1991). During the ablation season of 1982, measurements of discharge and suspended sediment concentrations of meltwaters draining from Gornergletscher into the Gornera were obtained at hourly and daily intervals which can permit the estimation of total daily sediment flux. Discharge (which is measured in m^3s^{-1}) and suspended sediment concentration (which is measured in Kg m^{-3}) are both multiplied together to give a 'flux' (Kg s^{-1}).

Suspended sediment loads in streams and rivers tend to be supply-controlled, whereas coarser bed load is hydraulically controlled. Stott and Mount (2007, p. 260) also mention that 'suspended sediment fluxes are likely to be more responsive to climate-driven environmental change, other factors being equal seasonal patterns of variation in sediment flux are interpreted in terms of development of the subglacial drainage network'. Variations in flux relate to contrasting temporal patterns of run-off, and the differing incidence of subglacial hydrological events. During such events, in which basal water pressure is raised, large areas of previously hydraulically isolated sub-sole are integrated with flow, releasing quantities of sediment from basal storage. Several types of methods for collecting sediment data are identified during periods of generally increasing discharge in the early ablation season, resulting from temporary blocking of subglacial passageways or from outbursts emptying a marginal, ice-dammed lake, and related to rain-induced floods (Collins, 1989).

Concentrations of total suspended solids and their associated fluvial fluxes are known to vary enormously over time and space (Meybeck *et al.*, 2003). Year-to-year changes in hydro-meteorological conditions can lead to inter-annual variations in run-off and subglacial entrainment of sediment by meltwaters. So ideally to enable comparisons between sediment fluxes close to glaciers with those at downstream locations, samples need to be taken at regular intervals, using the same technique, at the same station throughout the

same year. High daily fluxes occur in basins combining several factors of erodibility, such as very high runoff during floods, steep relief and occurrence of erodible materials (Meybeck *et al.*, 2003). It is mainly small quantities of sediment that continually enter the flowing meltwaters through melting of the channel, but on occasion, large quantities of sediment can enter the run-off and continue to flow in the meltwater which causes an instability in the hydrological system or can cause a sudden fluctuation in the data.

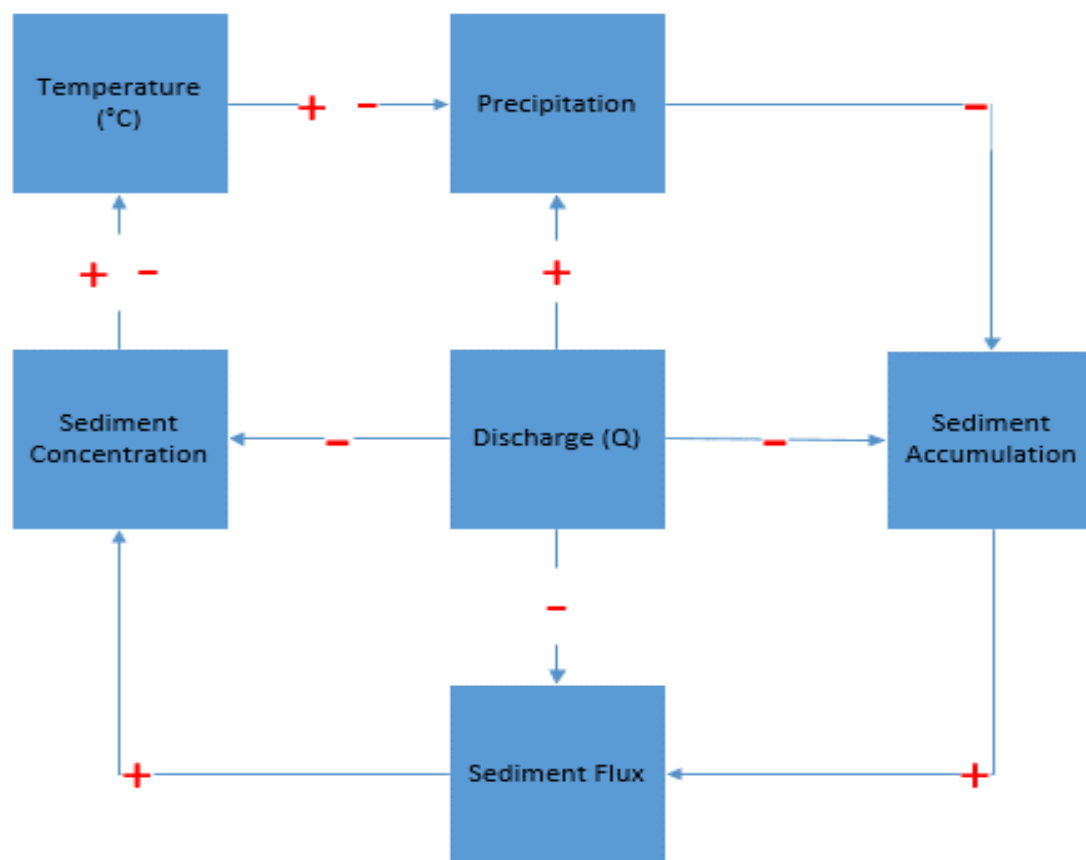


Figure 2.4: A flow chart created on Microsoft Visio showing positive and negative relationships between factors that can affect discharge and suspended sediment concentration patterns.

Many different factors influence the relationship between suspended sediment concentration and discharge for example temperature, sediment accumulation and precipitation (figure 2.4). Some influences are positive whilst others are negative and some

can be either. Discharge is an extremely important parameter affecting suspended sediment concentration so it is placed centrally in figure 2.4. Discharge is generally at its highest in the ablation season when ice/snow melt peaks, however, this has a negative effect on suspended sediment concentration as generally, higher discharge means lower concentrations (table 1.1).

Temperature also relates to sediment flux as it can influence both suspended sediment and discharge in different ways. If temporal conditions are cold (mainly in the accumulation season) discharge can still be high as precipitation tends to increase in the accumulation period, meaning it has a negative effect on sediment concentrations. If temperatures are mild (normally towards the end of accumulation season and beginning of ablation season), sediment concentrations could be at their highest as snow/ice is still in accumulation and ablation is just beginning meaning discharge would be low. There are many different factors that have positive or negative influences on sediment concentration and discharge (figure 2.4). Some factors can even have a positive and a negative effect such as temperature. A warming temperature can mean more discharge due to ice/snow melt, which has a negative effect on sediment concentration, and a colder temperature means less discharge which has a positive effect on sediment concentration.

2.4. Discharge

During the ablation season, diurnal variations of meltwater discharge from the portals of alpine glaciers are accompanied by roughly phased but inverse fluctuations of the dissolved content of the water (Collins, 1995). Meltwaters draining from the Gornergletscher catchments are of extreme importance in the Gornera region as it helps to produce hydroelectric power for villages nearby such as Zermatt, Switzerland.

This power station built by Grande Dixence in 1965 is one of the most significant advances in hydroelectric power not just in Switzerland, but worldwide because villages in Alpine regions depend upon glacier fed hydro-electric power schemes as an important source of energy. The Grande Dixence power station is the tallest gravity dam in the world (285m in height) and produces hydroelectric power to four power stations. This is also where discharge data was directly obtained and is located approximately 1 km downstream from the snout (Tranter and Raiswell, 1991). Measurements from this gauging station have been providing discharge data in the Gornera for over three decades and information provided is vital for carrying out high mountain research. The complex topography of the Alps makes detailed hydrological modelling a real challenge. It remains an essential task to improve the insight of hydrological processes in context of intensification of renewable energy use and under constraints of climate change (Uhlmann *et al.*, 2013).

There are many different factors that can affect discharge such as heavy precipitation and temperature (figure 2.4). However, one other influence that causes rapid increase in a short space of time is the outburst of a glacier-dammed lake. Since an enormous amount of lake water drains into the glacier bed within a short period, the glacier flow regime is expected to change dramatically during an outburst event due to the changing subglacial conditions (Sugiyama *et al.*, 2007). In general, glacier-dammed lakes start to drain when the lake level reaches its peak, however, this varies depending on the triggering mechanism from the outburst of the 'ice-dam' (glacier adjacent to the lake) caused by the pressure of the lake water initiates the drainage (Sugiyama *et al.*, 2008).

Sub-glacial water is of importance in both the hydrology and dynamics of glaciers. A hydrological network at the bed of a glacier must allow movement of water produced by melting at places with high pressure to places of low pressure where refreezing occurs, and permits the transfer of large quantities of melt water down-glacier. Variations in the rate of sliding of a temperate glacier are probably affected markedly by the availability of sub-glacial water (Collins, 1979). Figure 2.5 shows cumulative percentages of season totals of discharge and suspended sediment load in the Gornera between 1983- 1987.

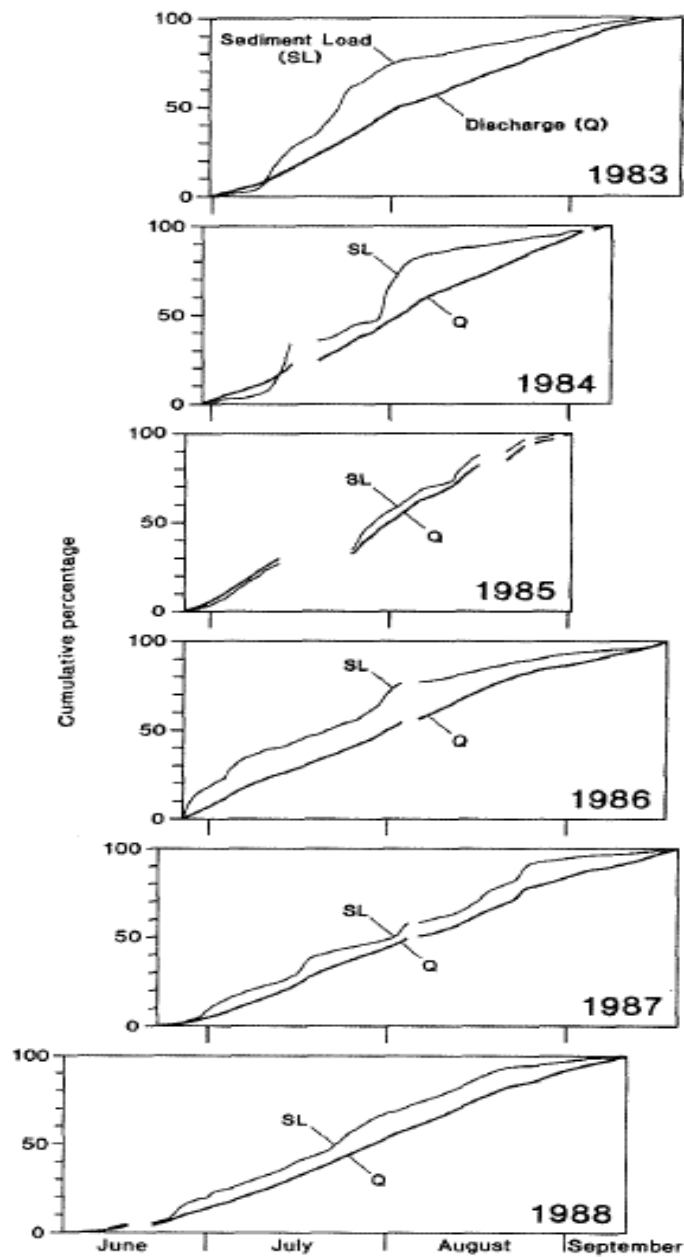


Figure 2.5: Cumulative percentages of season totals of discharge (Q) and suspended sediment load (SL) in the Gornera, which have passed the gauging station plotted by day through the measurement period. Where sediment measurements are missing, the concurrent corresponding discharge is not included in the accumulating runoff total (Collins, 1990).

2.5. Summary

Data collection in journals researching into suspended sediment and discharge have to be assessed on validity and accuracy. Climate plays a pivotal factor in how much discharge can drain into a glacial lake and also how much suspended sediment is transported downstream. Mass balance is extremely important in terms of glacial survival, and in order for mass balance to occur, the accumulation and ablation periods have to match each other. Haeberli *et al.*, (2007) believes that for the European Alps, climatic changes have been documented throughout history with observational records of local glacier mass balance. These climatic records can prove that mass balance is largely affected by changing conditions of a basin. Barry (1992) thinks climate change could greatly influence discharge from glacierised catchments, with river flow varying depending on global and regional warming. Journal papers tend to concentrate on one particular parameter instead of including multiple parameters, such as Haeberli *et al* (2007) and Barry (1992) solely focussing on climate change. Whereas, this paper includes several factors which all have an effect on climate change.

Changes in a glaciers area and volume could have an impact on water availability in certain catchments, changing both the amount and also release time according to Pellicciotti (2010, p. 1) which could also have an effect of suspended sediment transport. All journals related to this paper believe that discharge plays a large role towards suspended sediment transport, and during the ablation season, diurnal variations of meltwater discharge from the portals of alpine glaciers are accompanied by roughly phased but inverse fluctuations of the dissolved content of the water according to Collins (1995). Discharge data collected by the Grande Dixence power station (which is where discharge data was directly obtained from) is located approximately 1 km downstream from the snout (Tranter and Raiswell, 1991), and variations in the rate of sliding of a temperate glacier are probably affected markedly by the availability of sub-glacial water (Collins, 1979).

Ideally a more extensive network for suspended sediment in the Gorner region of Swiss Alps would give a better indication if there is a relationship between suspended sediment and discharge, however, suspended sediment loads in streams and rivers tend to be supply-controlled, whereas coarser bed load is hydraulically controlled. Stott and Mount (2007, p. 260) mention that 'suspended sediment fluxes are likely to be more responsive to climate-driven environmental change, whereas, Meybeck *et al.*, (2003) believe that concentrations of total suspended solids and their associated fluvial fluxes are known to vary enormously over time and space. Due to lack of research in this field, it is unclear to see which theory is correct as of now.

3. Study Area

The following chapter describes conditions which occur in the Gornergletscher area, where research for this thesis took place. Initial descriptions of Gornergletscher focus on physical characteristics and also through narratives for geographical and climatic settings. Section 3.1 describes the Gornera and Gornersee, including its location and other geological conditions, sections 3.2 and 3.3 describe the main study area and give a more detailed account of where data has been collected and other interesting features of that specific study area, and section 3.4 is a digital terrain model created using Geographical Information System (GIS) of the study area including elevation levels.

3.1. Gornersee and Gornera

Gornersee, Switzerland, is an ice-marginal lake (figure 3.1), which drains almost every year, sub-glacially, within a few days (Huss *et al.*, 2007). This lake is the main source of sudden meltwater release in the Gornera catchment area during ablation periods. Glacier-dammed lakes can release their water suddenly, causing a so-called outburst flood or 'jökulhlaup'. The Gornersee is located in the confluence area of two main tributaries Gornera and Grenzletscher. This lake has an elevation of 2530 m above sea level and lies 5.25 km up glacier from the terminus (Werder *et al.*, 2010). The Gornera is a glacier fed river that is the only pro-glacial stream draining from the snout of Gornergletscher. Meltwater eventually flows into the Gornersee, which is a lake that fills every year mainly through discharge and ice melt from Gornergletscher itself, and drains in the summer every year.



Figure 3.1: A photograph of the filled Gornersee taken in 2004 (Riesen *et al.*, 2009).

The Gornersee (figure 3.1) is relatively small with a volume of 1-4 mio m³ and a peak outflow of about 30 m³/s (Werder, 2006). The majority of this lake is ice floored and the

eastern part is dammed by bedrock. Gornergletscher has an elevation range from around 2200 to 4600 m.a.s.l and most parts of this glacier are temperate. However, Gornersee, which is a deep basin, has seen significant change of glacier geometry during the past Century and this has caused a shift in lake location and volume. The lake normally starts to fill during the beginning of May and tends to drain between June- August.

Glaciers are commonly used for understanding past, present and future climate change. Low-frequency climate change can be reflected in glacier length variations (Lemke *et al.*, 2007). Suspended sediment flux events in the Gornera are generally associated with, but can be independent of, increases in run-off induced by thermal conditions, rainstorms, and emptying of the Gornersee. Such increases in flow can trigger spatial instability in the drainage system beneath Gornergletscher (Collins, 1991). Each year 1 to 6 Million m³ of meltwater are impounded by this lake and drain sub-glacially within a few days. Peak discharge during outburst events, measured at the gauging station, reaches 20 to 50 m³s⁻¹, of which between 40% and 75% is lake water. In the first half of 20th century flood intensities of more than 100 m³s⁻¹ were reported, regularly causing severe damage in the valley of Zermatt (Huss *et al.*, 2007).

3.2. Gornergletscher

Gornergletscher, Valais, Switzerland, (45.97°N, 7.80°E) is the second largest glacier in the Swiss Alps (Holzhauser et al., 2005) and was chosen for study due to the multiple tributary glaciers, extensive previous study, and relative ease of access. The length of Gornergletscher has changed dramatically between 1880- 2015 (figure 3.2) but most dramatic change has occurred between 1950- 2010. The glacier extends from an altitude of 2150- 4500 m (Iken *et al.*, 1996) and consists of several tributaries covering an area of nearly 60 km². In the last Century, Gornergletscher (figure 3.3) has experienced significant ice loss, especially in the lake area (Bauder *et al.*, 2008) causing excessive melt water to enter the Gornera which is a river that consists of mainly ice-melt from the surrounding glaciers (Gornergletscher, Findelengletscher and Grenzgletscher). The Gornergletscher system is very dynamic and has experienced large changes during historic time.

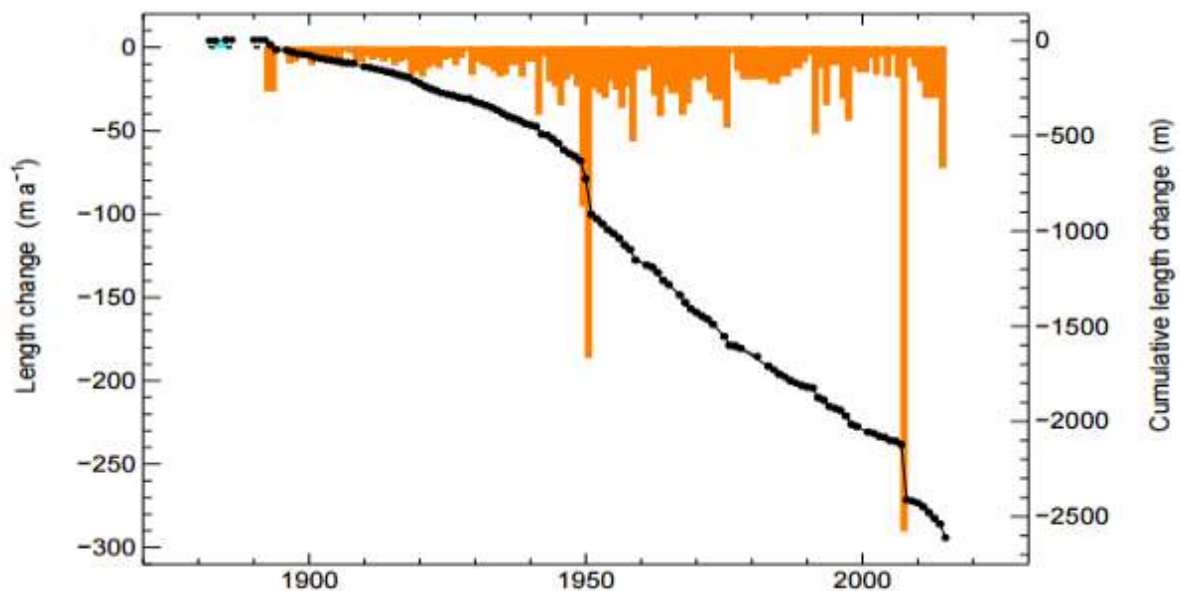


Figure 3.2: Annual changes in length (columns) and cumulative recession (black line of Gornergletscher between 1882 and 2015. Swiss Glacier Monitoring Service (GLAMOS).

Since the last maximum at the end of the Little Ice Age (1859), Gornergletscher was visible from Zermatt, but since, has advanced 10 m/yr destroying houses and farmland. Gornergletscher has retreated 2600 m since 1865 (Holzhauser *et al.*, 2005). Most meltwater is caught by a water catchment station of the Grande Dixence hydroelectric power company, which is an interesting feature of Gornergletscher. The tongue is supplied by ice originating from the highest regions of the Monte Rosa massif and substantial portions of this ice are still below the pressure melting point in the glacier tongue (Eisen *et al.*, 2008). According to the World Glacier Monitoring Service, the Gornergletscher system covered an area of approximately 38 km² in 2003, a dramatic decrease from approximately 68 km² less than decade earlier, as stated in the report for 1995-2015. Between 1931 and 2003, the glacier lost an estimated volume of 1.69 km³ (Haeberli *et al.*, 2007; Haeberli *et al.*, 2008).



Figure 3.3: A photograph of Gornergletscher taken from the tongue in 2004 (Eisen *et al.*, 2008).

Samples of suspended sediment have been collected from the Gornera, which is the only river that drains from Gornergletscher. These samples were collected from the gauging station which can be seen on figure 3.4. However, as Gornergletscher has retreated increasingly over time, this gauging station has now moved 1.5 km further up the glacier. During the ablation season of 1982, measurements of discharge and suspended sediment concentrations of melt waters draining from Gornergletscher, Switzerland (figure 3.5) were collected at hourly and daily intervals, which allow estimations of total daily sediment flux to be created.

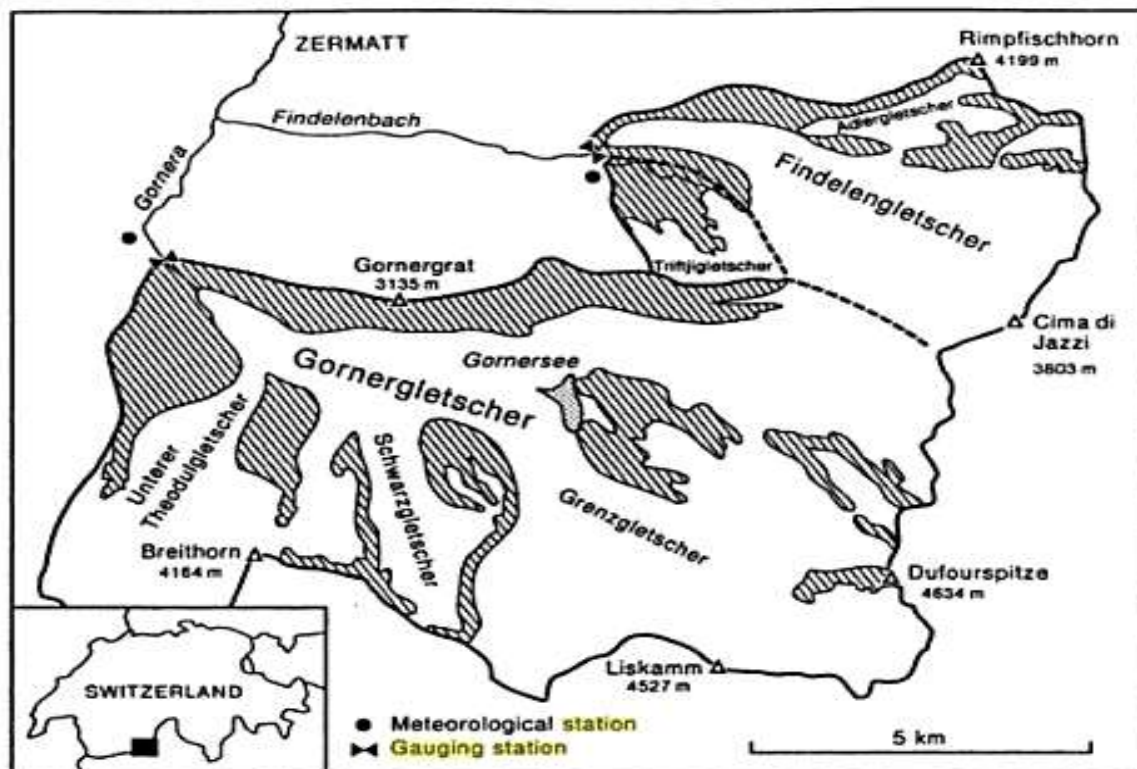


Figure 3.4: Map of basins including Gornergletscher and Findelengletscher, showing locations of the gauging station on the Gornera where data has been collected (Collins, 1989).

Seasonal patterns of variation in sediment flux are interpreted in terms of development of the subglacial drainage network (Collins, 1989). Variations in flux can relate to contrasting temporal patterns of run-off, and the differing incidence of subglacial hydrological events in the ablation season of 1982. Pressure from basal water is raised meaning large quantities of sediment from basal storage are released and added in with the flow, increasing sediment transportation. Transport of sediment in melt waters draining from glaciers which do not surge are produced by high flows resulting from periods of sustained ice melt, and following heavy rainfall events (Østrem, 1975).

3.3. Digital Terrain Model.

A digital terrain model has been created to help show different elevation bands around the Gornergletscher region (figure 3.5). The map consists of two contrasting glacier catchments, (Gornergletscher and Findelengletscher) but Gornergletscher has a greater catchment area, more meltwater is produced than Findelengletscher, leading to a cooler temperature of the Gornera. As Findelengletscher has a slightly smaller surface area (19 km²), there are smaller discharges coming from the glacier and surrounding areas.

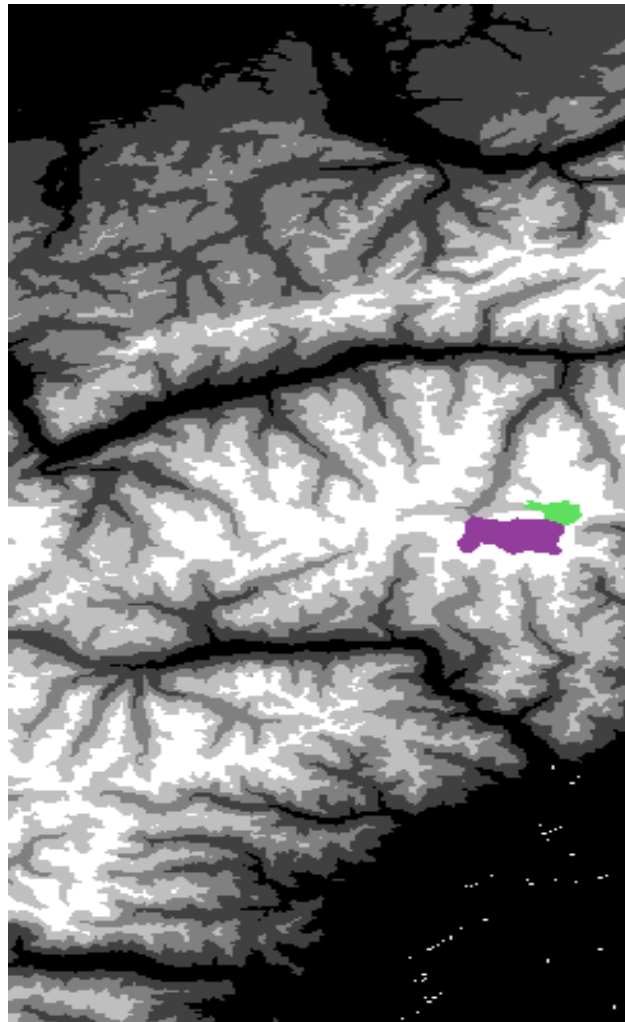


Figure 3.5: ArcMap image of Gornergletscher (Purple) and Findelengletscher (Green) with elevation levels included (darker colour represents low-level height and lighter colour represents high elevation levels).

Geographical Information Systems (GIS) provide visual representations of a specifically chosen area such as Gornergletscher. GIS can also examine changes in glacier thickness and volume dating back from as long as the late nineteenth Century through many different tools on this system. However, GIS have helped this study in other ways, for example distinguishing a total area of Gornergletscher to help find the main channel that flows into the Gornera.

4. Methods

Professor D. N. Collins from the University of Salford provided data from records held by the Alpine Glacier Project. Instruments were mounted on the Gornera gauging station, which is located 1.5 km down river from the terminus of Gornerglletscher. Sediment transfer studies should be undertaken as close as practicable to the terminus of a glacier in order to minimise impact of runoff and sediment supply from valley sides of the non-glacierised portions of the basin (Srivastava *et al.*, 2014).

4.1. Approach

The ablation season of 1982 was selected for study as this year was the first of many warm summers (figure 4.1) and there were minimal gaps in suspended sediment concentration data collected compared to other contrasting years. Measurements involving physical collection of sediment samples at hourly intervals were available, together with continuous photoelectric determinations of turbidity, and daily samples of 50 L of meltwater and sediment. Sections 4.2 - 4.4 give a detailed account of three different methods of data collection, explaining apparatus used for each which justify their use.

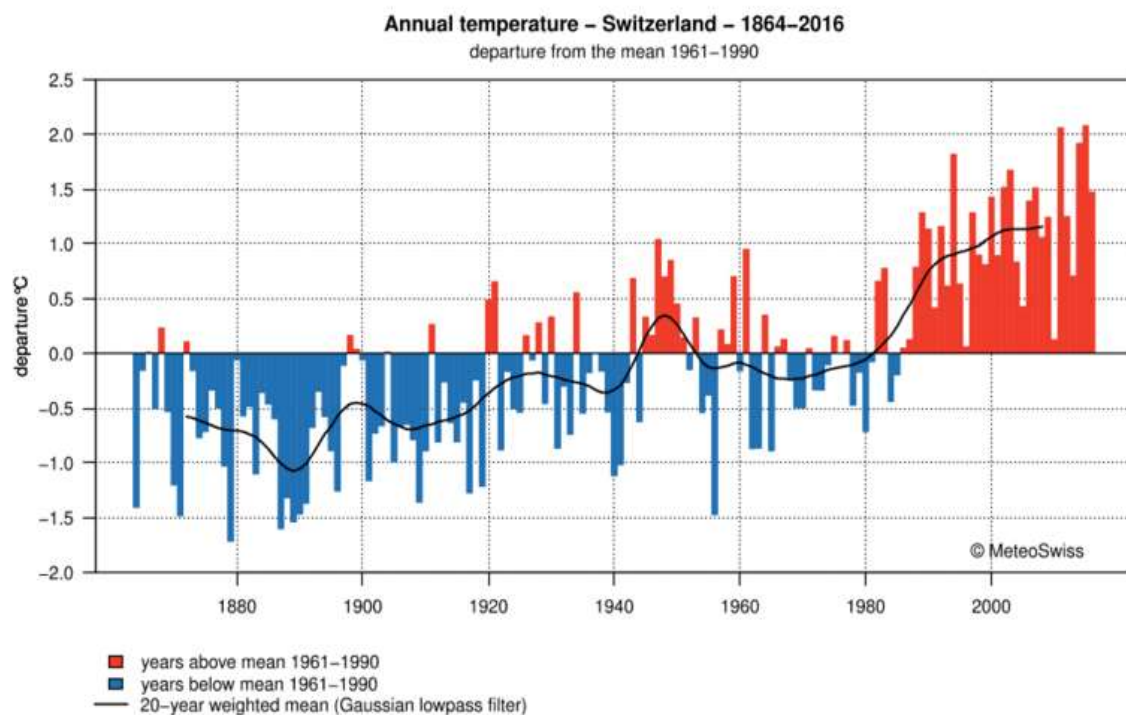


Figure 4.1: Climate trends illustrate the development of temperature and precipitation in Switzerland since the beginning of systematic measurements in 1864. The deviations of the annual and seasonal values from the average of the period from 1961-2990 (normal period) are illustrated. Meteo Swiss (2017).

4.2. Photoelectric Suspended Sediment Monitor

Suspended sediment concentrations were collected every two seconds by a Rustrak chart recorder (figure 4.2) that is attached to a portable turbidimeter (Partech 740) photoelectric suspended sediment monitor on selected days for 1982 (figure 4.3). Rustrak recorders imprint a signal output by the Partech monitor as an analogue record on pressure sensitive paper (figure 4.4). This method of data collection is not labour intensive as data are continuously recorded on a scale of 0- 10 cm, so that calibration against measured concurrent suspended sediment concentration is required. In Partech active head sensors, a pulsed signal is used to obtain a direct current with a fixed 'off' period and a variable 'on' period whose length depends on turbidity.

There are few limitations in using photoelectric data as a method of measuring suspended sediment concentrations, however, one limitation is that the instrument can be left to record by itself. As a result of this, suspended sediment could block the sensor head, causing a continuous zero value to be recorded until there is human intervention. Size of vision of the monitor is 2 ml and the sample window is only small by comparison with the sediment cones and the sample needs calibrating as there could be continuous readings of zero. Apart from these two limitations, photoelectric sediment data has proven to be a very popular and reliable method of data collection for decades and will more than likely be used in future studies.



Figure 4.2: Rustrak recorder that prints data onto pressure sensitive paper on a scale from 0- 10 cm.



Figure 4.3: Partech Suspended Sediment Monitor and sensor head used to collect data from the Gornera in 1982.

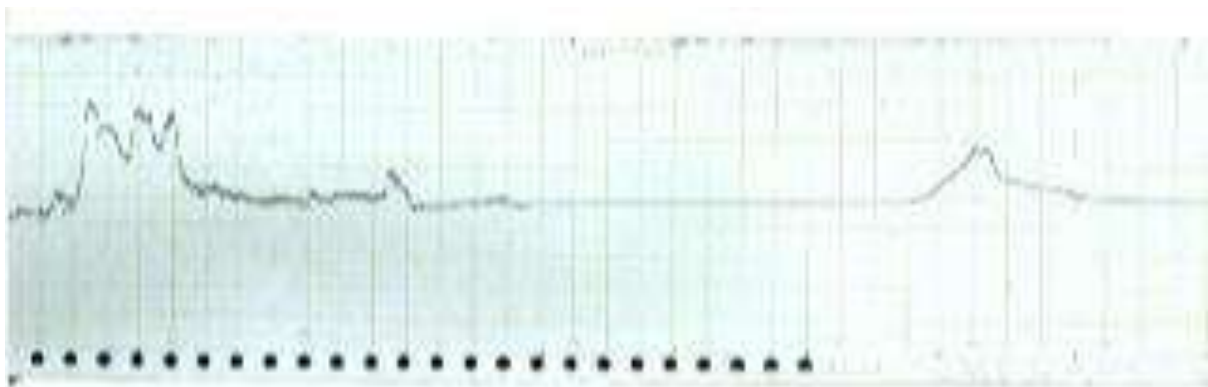


Figure 4.4: Scanned image of pressure sensitive chart used to record turbidity data from Partech Photoelectric System. Every two seconds a stylus is pressed against the chart by a chopper bar in a Rustrak chart recorder.

4.3. Manning Automatic Liquid Sampler

Suspended sediment concentrations have been collected from the Gornera region of Switzerland by using a Manning automatic liquid sampler (figure 4.5). The sampler comprises a number of bottles initially filled with discharge and sediment to be sampled. Each bottle is connected to a central suction pump with an adjustable uniform flow-rate by an electro-valve controlled by a programmed clock, and each bottle is also fitted with a tube conveying liquid to it from a container. This forms part of a branch circuit from the main flow of liquid; and the tube siphons the liquid into each bottle, that contains an aperture above the maximum level reached by the sample fluid. The Manning automatic liquid sampler can help to determine whether glacial meltwater streams carry particularly high concentrations of fine material in suspension, as a result of both glacial abrasion and channel migration which increases sediment availability in the flow that maintain transport (Clifford *et al.*, 1995).



Figure 4.5: Manning automatic liquid sampler taking samples of discharge and suspended sediment.

Small quantities of fine sediment are continually supplied to meltwaters during the ablation season through frictional melting of the basal ice layer above flowing threads of water and of the margins of passageways, allowing meltwater to move laterally onto stored basal sediment. Some sediment will be deformed into meltwaters at channel margins and glacier sliding will position further debris-rich basal ice over flowing meltwater and transfer ice-walled conduits onto unworked areas of bed (Collins, 1990). Suspended sediment concentrations in meltwater rivers have become increasingly important in recent years and records of streamflow discharge are equally as important in order to suggest there is a relationship between sediment concentration and discharge.

Concentration of sediment in water flowing in any river almost inevitably declines with increasing discharge (table 1.1). When this pattern of behaviour occurs, it is known as the 'dilution effect'. The suspended sediment concentration/discharge relationship or rating curve for a drainage basin reflects the overall pattern of erosion and sediment delivery operating in the upstream area and provides a useful and readily accessible starting point for isolating and interpreting salient features of basin sediment response (Walling & Webb, 1982). Minimum solute concentration and maximum discharge may not occur simultaneously and vice versa due to fluctuations in precipitation. This effect accompanies floods in temperate rivers, but due to the diurnal regime of the melting of snow and ice to form meltwater discharge, solute tends to fluctuate with discharge every-day in glacier fed streams. Figure 2.4 shows a relationship between sediment concentration and discharge and also sediment flux which is the mass of solute being carried at one time and is equally as important as it forms a time-series for the sediment concentration/discharge relationship.

Spatial instabilities suddenly inject much larger quantities of suspended sediment to meltwaters. In spring, fluctuations of suspended sediment in portal meltwaters are consistent with flushing of large areas of subsole as drainage is initiated (Collins, 1988 and 1989). Small amounts of sediment enter run-off flow through frictional melt of channel margins, but large amounts of sediment occur over several days of melt-water flow. Links between suspended sediment with discharge and climate variations can mainly be identified

when studying areas consisting of warm base glaciers, as these types of glaciers are constantly mobile resulting in higher rates of erosion and transportation throughout the year compared to colder based arctic glacier basins (Haritashya *et al.*, 2006).

Suspended sediment transport in meltwaters, which drain from high mountain glaciers, can vary considerably each year. There are many factors which can affect the concentrations of sediment including differences in spring and summer weather conditions which can result in contrasting seasonal patterns of discharge and differing rates and extents of development of the subglacial drainage system (Collins, 1991). Similar to photoelectric suspended sediment monitor, the Manning automatic liquid sampler also collects small sample sizes of around 200 ml per sample. There are Manning automatic liquid samplers that can collect continuous samples, however, the rate of sampling can be adjusted, and in this case the samples are measured at hourly intervals.

4.4. Sediment Cones

One other method of collecting suspended sediment data was through the use of sediment cones. 50 L of meltwater were collected in 13 L buckets at about the same time of day, largely between 14.00 and 15.00h every day. Each cone has a Perspex tube, about 10 cm diameter, and 40 cm in height, into which over a period of about 24h sediment settles out. A 13 L bucket was dropped into the gauging station flume and then used to fill the cone topping up to a band indicating 50 L of collected meltwater. The height of the column of sediment accumulated in the Perspex tube was measured to indicate sediment concentration.

This method is very labour intensive, as all work has to be completed manually with a sediment cone. There will also only be one sample per day, whereas the other methods of data collection are collected every two seconds (photoelectric suspended sediment monitor) and every hour (Manning automatic liquid sampler). One positive of using this method of data collection is that data is reliable due to it being collected manually, whereas other methods of data collection are automatic so if a problem occurs, it can be rectified straight away whereas the photoelectric and Manning data cannot. One advantage of using sediment cones is that a sample size is much larger than the photoelectric and Manning data, and the bigger the volume of water, the more it is likely to represent actual conditions of the river. However, more frequent samples are more likely to pick up variations of the river over time.

Figure 4.6 shows a sediment cone and the measurements inside can range from 2-1000 ml. There is also a stopper on the bottom of the cone to facilitate removal of sediment and cleaning. The sample is completely manual as there is no technology involved in collecting the sediment and the colourless cone is made from transparent styrene-acrylonitrile S.A.N polymer with moulded graduations which dips into the stream to collect the sample.



Figure 4.6: Suspended sediment cone on the gauging station at Gornera that is being held upright by a tripod.

A schematic table has been created (figure 4.7) to give a general idea of which method of data collection is most suitable to use over frequency of collection, sample size, accuracy of sample, and amount of effort taken to collect a sample. The Manning automatic liquid sampler and photoelectric data were quite similar as they are both accurate methods due to how frequently samples are collected and require minimal effort to collect data as they record automatically. Sediment cones are completely different to the other two methods as they record data less frequently (once a day) and require more effort to collect samples as data is collected manually. Sample size is also different as sediment cones have a much larger sample size than a Manning automatic liquid sampler and a photoelectric suspended sediment monitor.

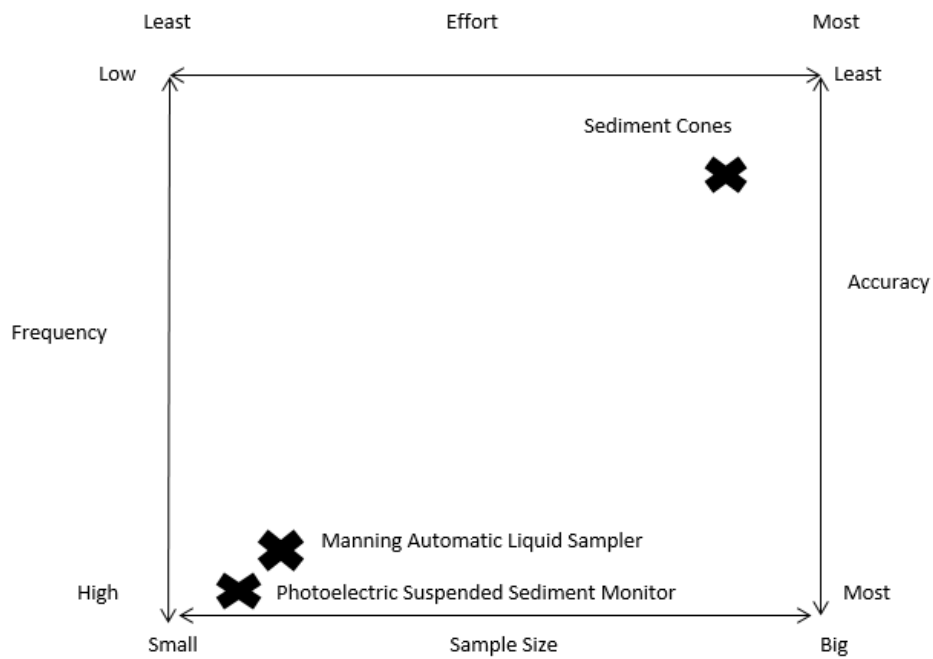


Figure 4.7: Schematic table comparing three different methods of sediment measurement techniques including effort, frequency, sample size and accuracy.

4.5. Data Calibration

Due to all three methods of data collection being measured in different units, data had to be calibrated into the same units in order for a direct comparison to be made. As the Manning automatic liquid pump sampler is the original method of collecting suspended sediment, it was necessary to calibrate the two other methods (photoelectric suspended sediment monitor and sediment cones) into the same units as the Manning (kilograms). For this to be made possible, the sediment load was calculated for the Manning method. In order to calculate suspended sediment load, multiply suspended sediment concentration (mg/ L) x Q (discharge) (m³/ s) = mg/ s. These can then be multiplied up to mg/ min (x 60), mg/ h (x 60), mg/ day (x 24) and best to divide by 1000 to get g/ day, and divide by 1000 again to get kg/ day.

Due to the photoelectric suspended sediment monitor originally recording the colour of water, this method has no meaning until it is calibrated into the same units as the Manning method (kg/ day). In order to convert photoelectric suspended sediment data into kg/ day an equation had to be inserted using Microsoft Excel '=2.78 x photoelectric data - 57.35'. This formula then has to be multiplied by discharge in order to get the suspended sediment load (mg/ s). This can now be directly compared to data collected using the Manning method.

To convert sediment cones into kg/ day, it was much more difficult than the photoelectric method. Firstly, the weight (mg) has to be divided by 50 in order for the unit to be mg/ L. This has to be now multiplied by discharge at the exact time of which the sample was collected. This should provide the suspended sediment load in mg/ s and it can now be compared with both other methods. As sediment cones collect only one sample per day, daily totals had to be calculated in order for a homogenous comparison to be made, and the unit used for all three methods would be kilograms per day.

One further problem with the data collection was due to the Manning and photoelectric methods collecting data automatically, which provided some errors within data that had to be deleted. This has effectively left some gaps within data which also had to be taken out for all three methods in order for a direct comparison to be made. These gaps will more than likely cause the 'R²' to decrease due to less data points being in the series, which in turn reduces the representativeness of the series. Data gaps within the time series also affect how accurate a method appears, as the more gaps within a series, the less accurate the method due to the sample being less representative.

Many factors can determine the accuracy of a method, for example data gaps, how frequent data is collected, sample size, and the less gaps, larger the sample and more frequent a sample is collected, the more accurate a sample will be. It is extremely difficult to achieve a completely accurate (or perfect) sample, as there are too many parameters, for example, it would appear to be more accurate if data was collected manually, however, in order to do this, it would cost more money, so most methods collect data automatically. One permutation of collecting data automatically is that if there is a problem with apparatus, there is no human intervention there to repair it, meaning data gaps will appear within findings.

5. Results

Suspended sediment concentrations have been collected using the three methods; Photoelectric suspended sediment monitor, Manning automatic liquid sampler and sediment cone. Discharge data has also been collected by the Grande Dixence, and only one study site was focussed on at the Gornera River where a selection of graphs including statistical significance, correlations, daily totals and daily averages are included. From 10 July- 29 August 1982 was the time period chosen for a number of reasons as data from all three methods was available to enable a valid and non-biased investigation. The graphs, together with the accompanying discussion and conclusion convey the salient characteristics of the potential relationship between suspended sediment concentration and discharge data to help distinguish a most suitable method of data collection out of the three used in this study.

There are few different reasons as to why there are various fluctuations in discharge (figure 5.1). The first is that being warm periods which increase ice melt causing discharge to increase rapidly over short periods of time. Another reason could be heavy precipitation entering a proglacial stream. One further reason as to why there is rapid increase over a short time period could be the main dam which was built by the Grande Dixence Hydroelectric company releasing a build-up of melt water and precipitation at once.

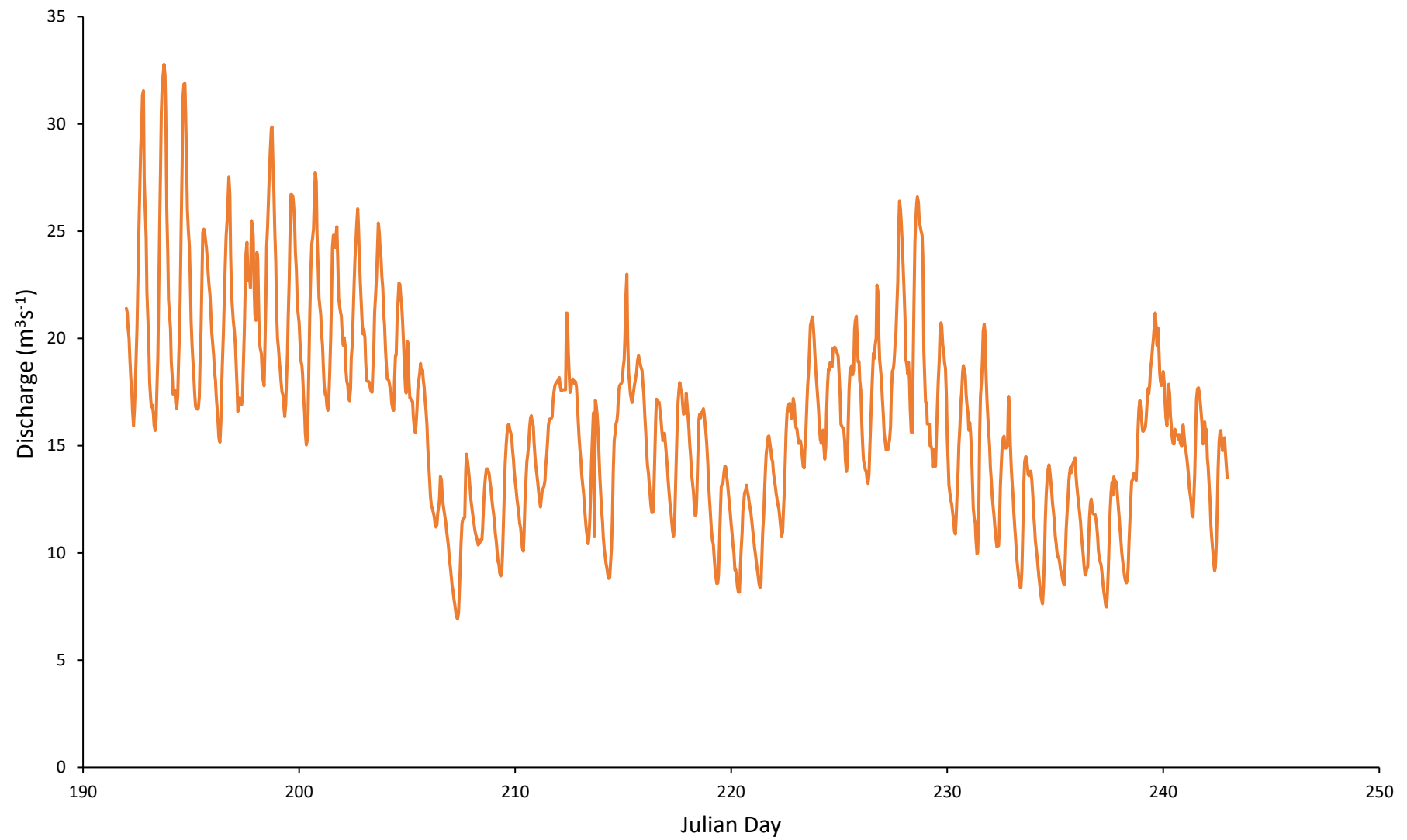


Figure 5.1: Hourly values of discharge in the Gornera between 10 July and 29 August 1982 (192-242).

Discharge is at its highest in early July on figure 5.1 between 11- 24 July (192- 204) due to the transient snowline rising to a high elevation causing increasing levels of discharge to occur. However, this may not be the case as discharge could be determined by the preceding winter snow conditions. Highest discharge of the season was attained on 12 July (193) as it peaks to $32.7 \text{ m}^3\text{s}^{-1}$ which is unusual as radiation tends to peak around 21 June as it has the longest amount of daylight compared to any other day. Flow then decreased to as low as $6.9 \text{ m}^3\text{s}^{-1}$ on 26 July (207). Discharge stays relatively low for a short period until 3 August (215) where a slight increase occurs, raising discharge to as high as $23.0 \text{ m}^3\text{s}^{-1}$. Diurnal variation occurs regularly during figure 19 and after the fluctuation on day 215, discharge is steady until two fluctuations occur in quick succession on 15 and 16 August (227 and 228) where a reading of $26.5 \text{ m}^3\text{s}^{-1}$ was recorded. After two fluctuations in discharge occur, once again, discharge dips relatively low for a short period of time until a final pulse then occurs on 27 August as a reading of $21.1 \text{ m}^3\text{s}^{-1}$ was taken.

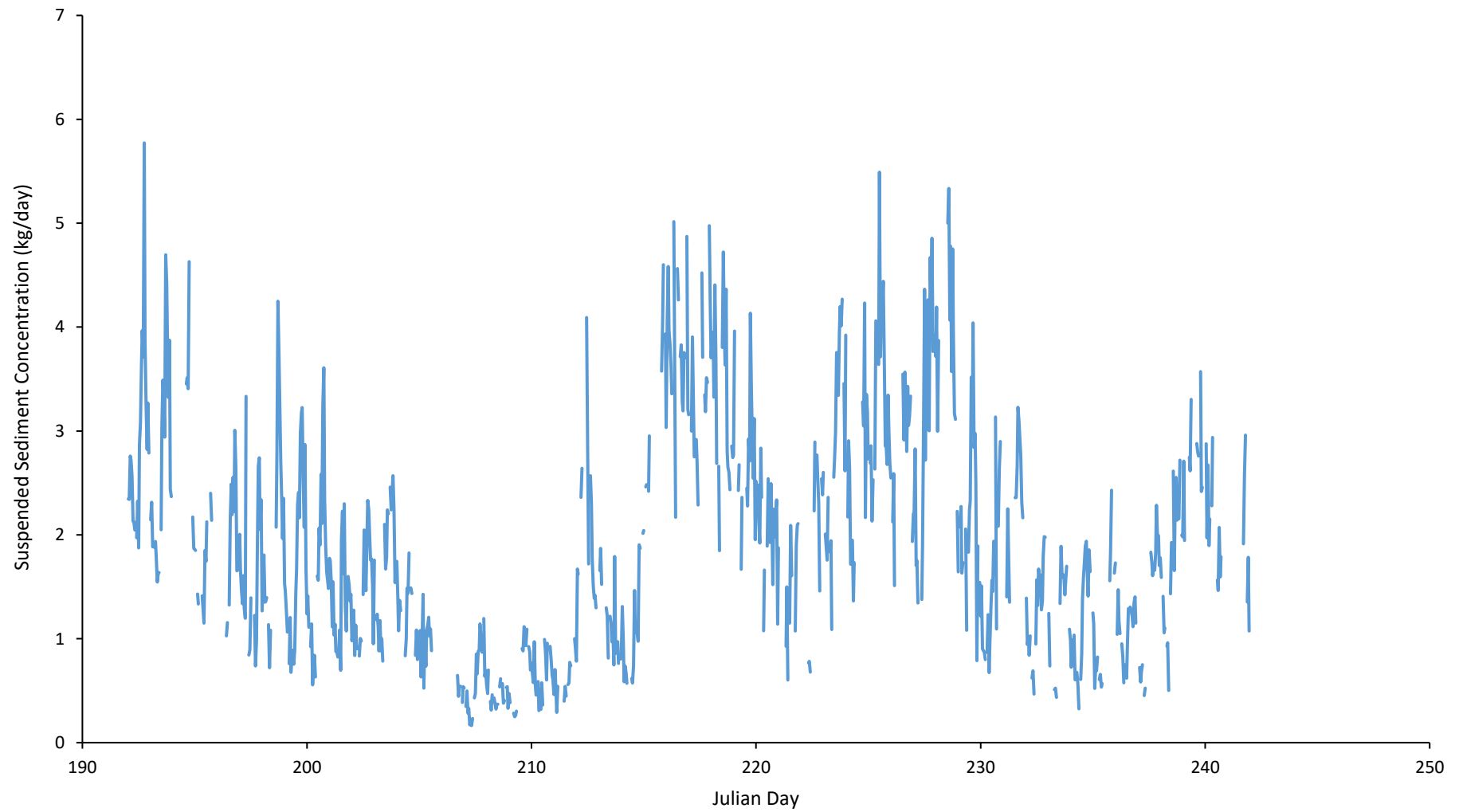


Figure 5.2: Hourly values of suspended sediment concentration derived from a Manning automatic liquid sampler between 10 July- 29 August (192-242) in the Gornera 1982.

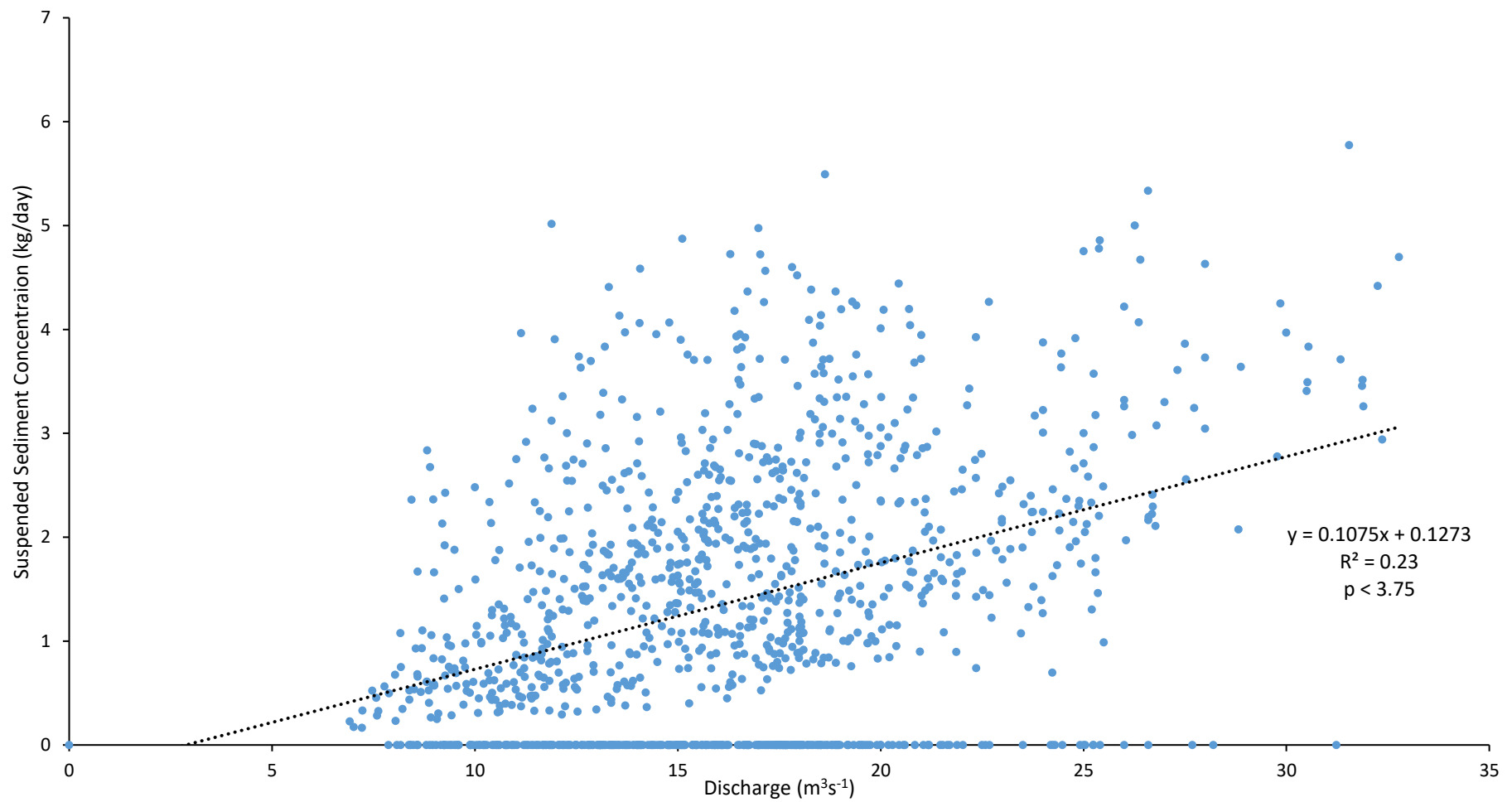


Figure 5.3: Relationship between suspended sediment concentration derived from a Manning automatic pump sampler and discharge measured at hourly intervals between 10 July- 29 August (192- 242) in the Gornera 1982.

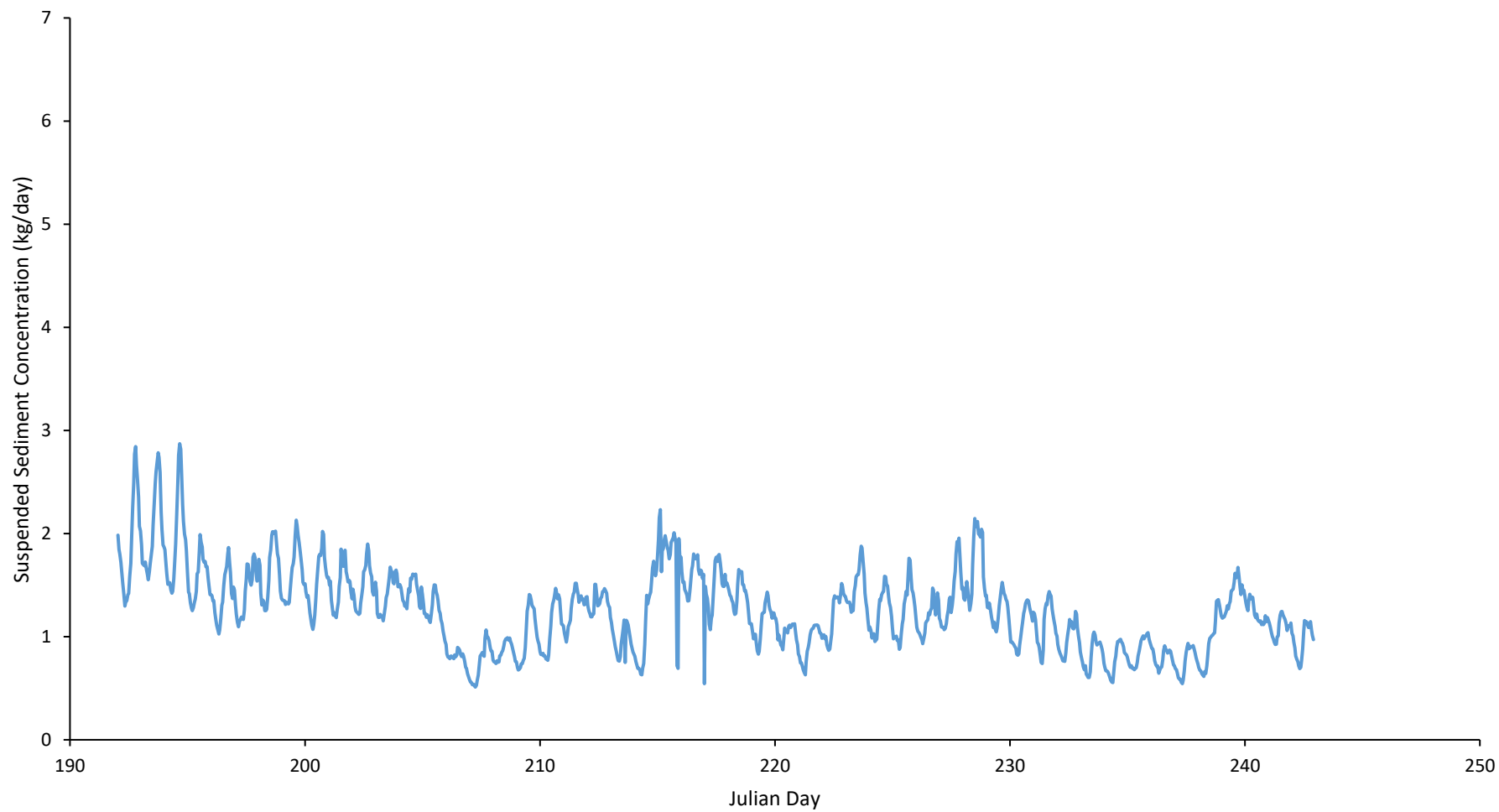


Figure 5.4: Hourly values of sediment content of meltwater collected by a photoelectric suspended sediment monitor in the Gornera between 10 July- 29 August (192- 242) 1982.

Between 10 July- 29 August 1982 (192- 242) suspended sediment concentration deriving from a Manning automatic liquid sampler was measured at hourly intervals for the Gornera (figure 5.2). Suspended sediment concentration actually peaks on the first day (192) at 18:00 as a measurement of 5.77 kg/day was attained. Sediment concentration then steadily decreases and the lowest reading of this time series was collected at 08:00 on 26 July (207) where a reading of 0.16 kg/day was taken. Concentrations stay relatively low until 18:00 on 2 August (214) where a fluctuation occurs and concentrations rise to 5.02 kg/day at 08:00 on 4 August (216). A large decrease in suspended sediment occurs after 4 August (216) as concentrations drop to 0.68 kg/day at 10:00 on 10 August (222), but then once again fluctuate to 5.49 kg/day at 12:00 on 13 August (225). This is the second highest reading of this time series. Suspended sediment concentration steadily decreases after 13 August (225) and the time series eventually finishes on 29 August (242) with a reading of 1.07 kg/day.

A scatter plot has been created to help distinguish how well suspended sediment concentration collected by a Manning automatic liquid sampler and discharge correlate between 10 July and 29 August 1982 (192-242) (figure 5.3). Results show a poor relationship between the two variables during this time period as shown on the trendline. The p- value ($p = < 3.75$) is much higher than the alpha (0.05), and the R^2 shows little correlation (0.23), which confirms that the correlation between suspended sediment concentration deriving from a Manning automatic liquid sampler and discharge is not statistically significant.

Suspended sediment concentrations derived by photoelectric methods produced a long record between 10 July (192) and 29 August (242) (figure 5.4). There are three large fluctuations at the beginning of this time series, the first one occurs at 18:00 on 10 July (192) where a measurement of 2.8 kg/day was attained. The second fluctuation occurs at 18:00 on 11 July where once again a measurement of 2.8 kg/day was collected. The final fluctuation is the highest during this time series and suspended sediment concentration

peaks at 2.9 kg/day at 16:00 on 12 July. Concentrations are continuously steady until 26 July (207), where suspended sediment is minimal and the lowest reading of this time series was collected at 06:00 that measured at 0.5 kg/day. Concentrations once again fluctuate to 2.2 kg/day on 3 August (215), but then steadily drop after this measurement until 9 August (221) where a measurement of 0.6 kg/day was attained and then suspended sediment concentrations were then continuously steady until the end of this time series where a final reading of 1.0 kg/day was collected at 22:00 on 29 August (242).

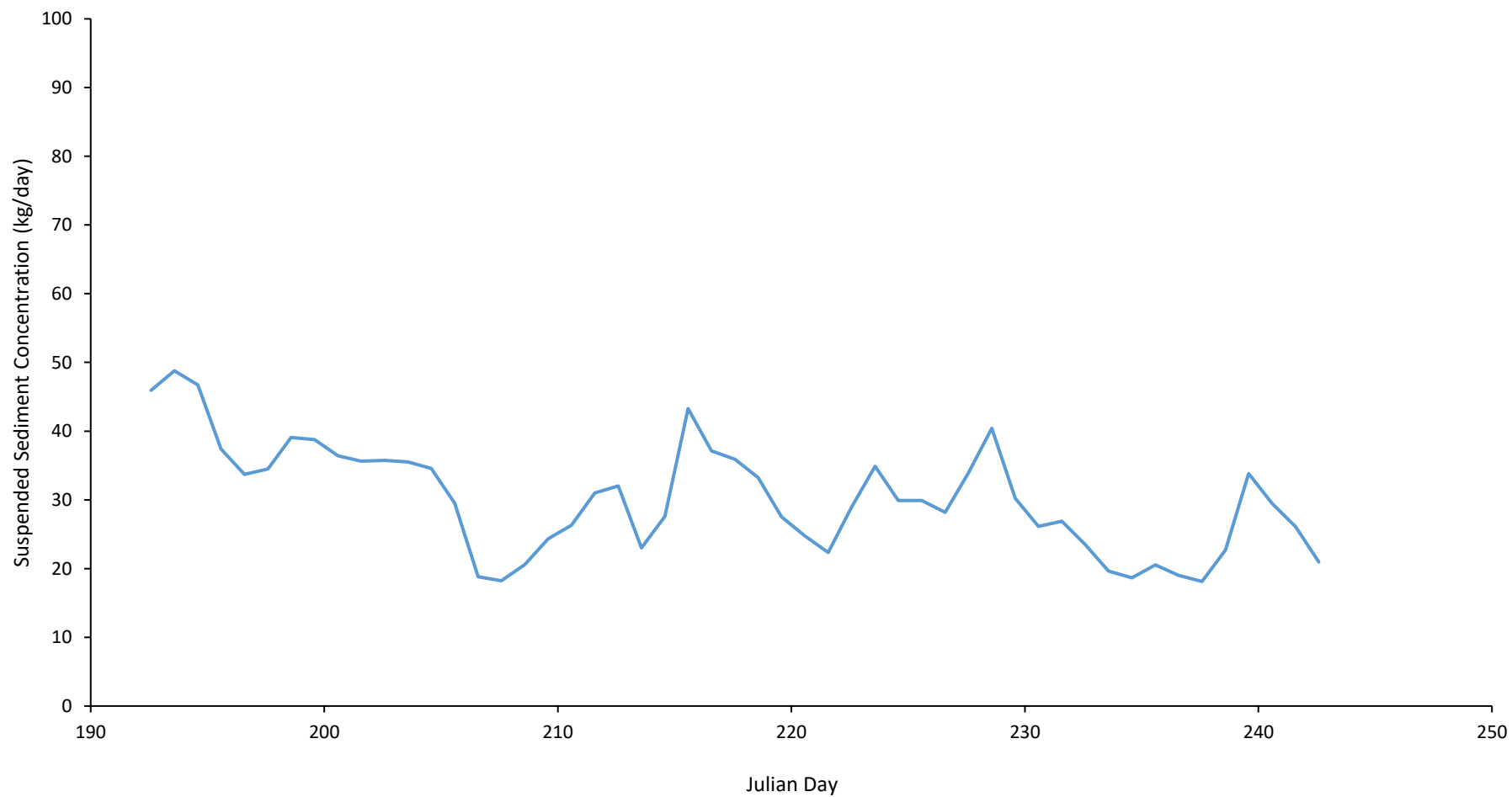


Figure 5.5: Daily totals derived from a Partech phototelectric suspended sediment monitor in the Gornera between 10 July- 29 August (192-242).

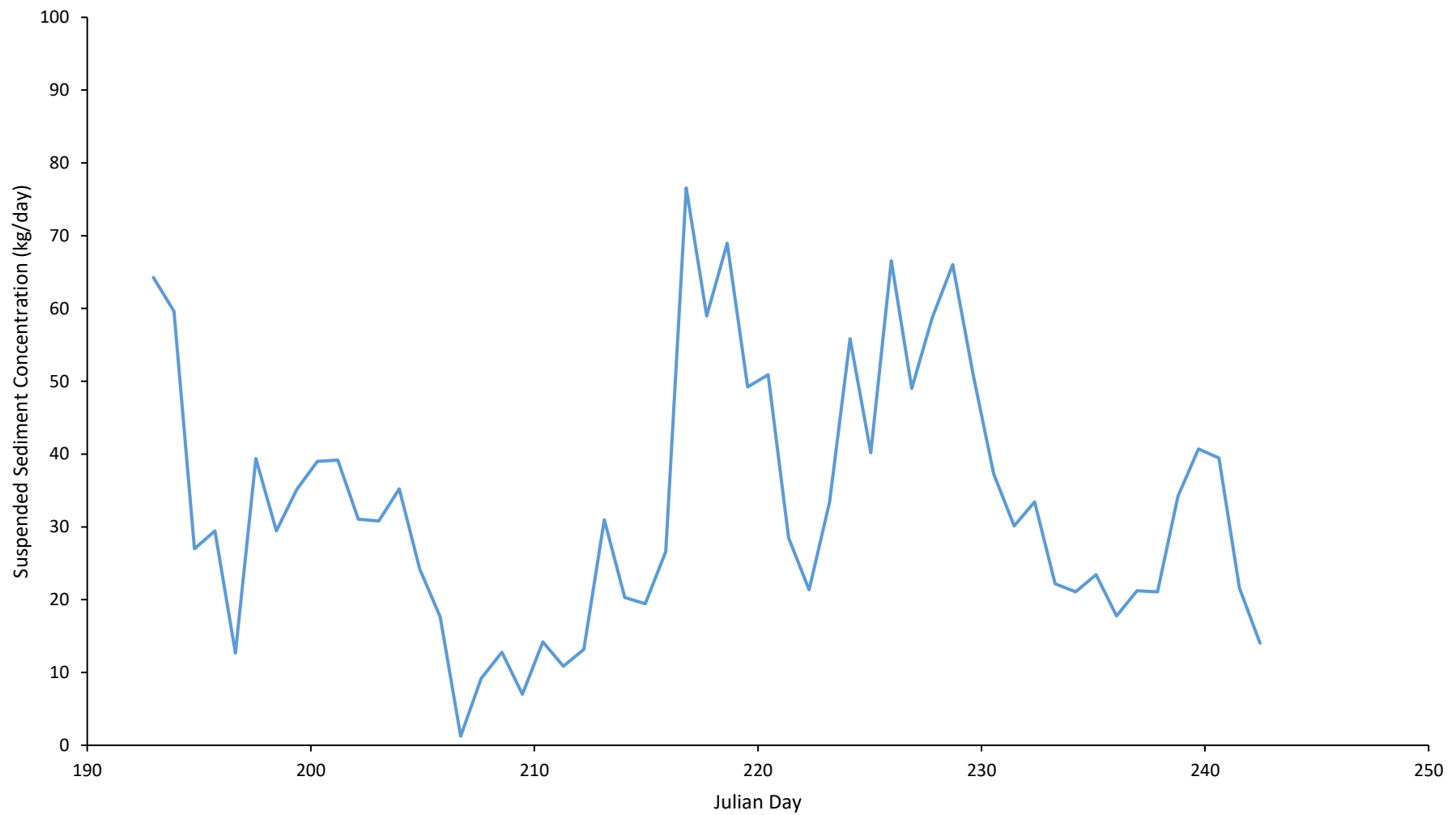


Figure 5.6: Daily totals of suspended sediment collected by a Manning automatic liquid pump sampler between 10 July- 29 August (192-242).

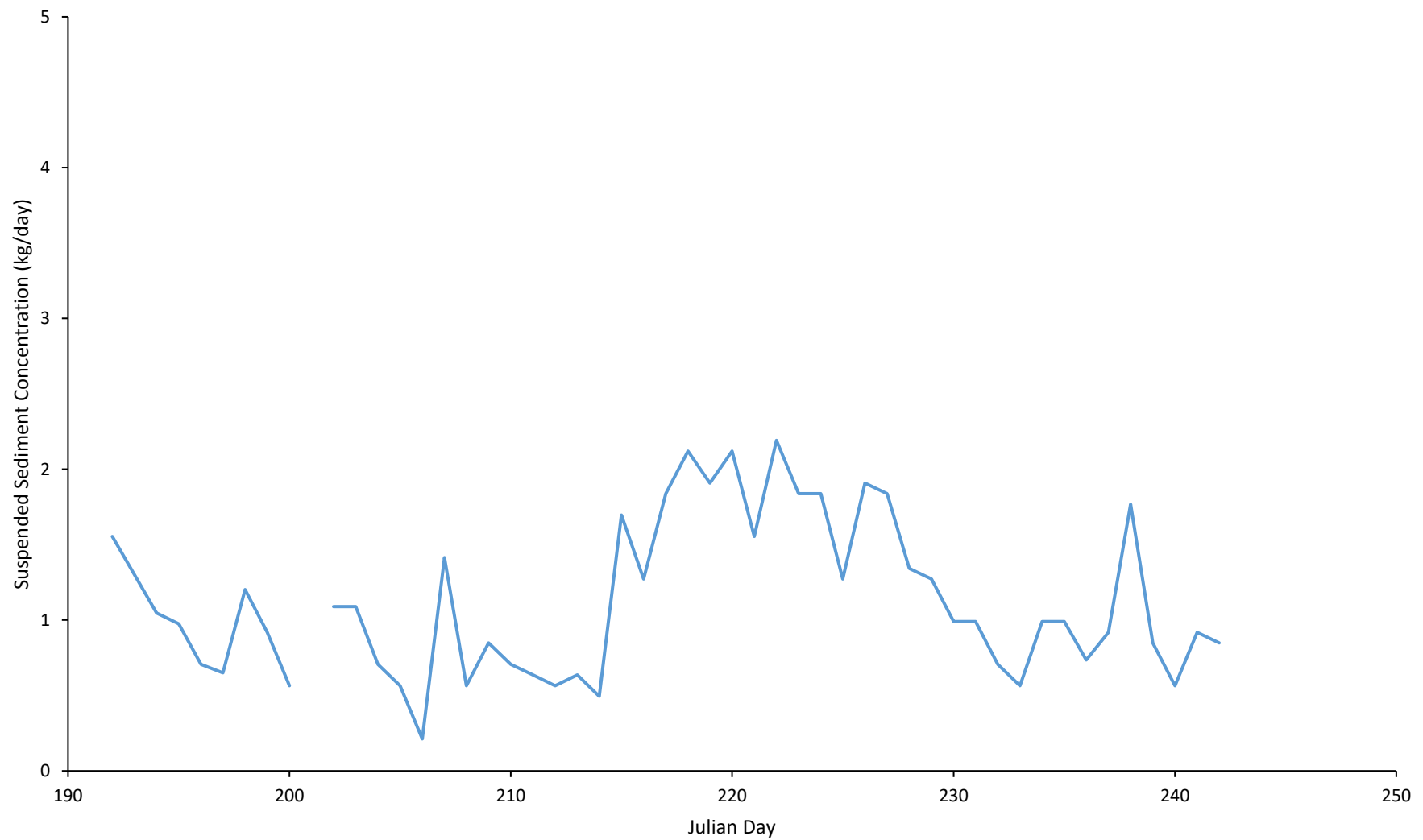


Figure 5.7: Daily values of sediment concentration derived from sediment cones between 10 July- 29 August (192-242) 1982 in the Gornera.

Daily totals of suspended sediment have been collected by a Partech photoelectric suspended sediment monitor between 10 July (192) and 29 August (242) for the Gornera (figure 5.5). Diurnal variation occurs throughout this figure between the two variables, and concentrations peak at the very start of this time series with a measurement of 48.7 kg/day on 11 August (193), however, suspended sediment steadily decreases each day up until 17 July (198), when suspended sediment starts to gradually increase once again. Daily totals then stay at a relatively steady level until 24 July (204) where large decrease occurs and sediment load troughs on 26 July (207) as a measurement of 18.21 kg/day was attained. Between 26 July and 3 August (207- 215) there is a fluctuation in suspended sediment, and the daily totals increase from 18.21 to 43.29 kg/day. However, after 3 August (215) suspended sediment decreases significantly from 43.29 to 22.35 kg/day on 9 August (221). There are two further fluctuations in suspended sediment towards the latter stages of this time series on 16 August (228) where sediment load reaches 40.42 kg/day and 27 August (239) and the daily total measures 33.84 kg/day.

Daily totals of suspended sediment concentration deriving from a Manning automatic liquid sampler were collected between 10 July (192) and 29 August (242) for the Gornera (figure 5.6). From 10 July- 15 July (192- 197) there is a relatively large decrease in suspended sediment load as the daily total decreases from 65.42- 12.67 kg/day. However, on 16 July (198) diurnal variation occurs as suspended sediment as the daily total rises to 39.83 kg/day. Between 22- 24 July (204- 206) suspended sediment troughs as the daily total decreases from 35.62- 2.57 kg/day. Daily totals then gradually increase consistently and eventually peak on 5 August (217) to 79.38 kg per day. Another drop in suspended sediment occurs on 10 August (222) where daily totals drop to 21.57 kg/day, however, there are three surges in quick succession in suspended sediment on 12, 13 and 16 August (224, 226, 229). Daily totals of suspended sediment then continuously decrease until 28 August (240) where there is one last surge which reaches 41.56 kg/day, then sediment gradually decreases after this until the end of this time series.

Samples of suspended sediment have been collected once a day by sediment cones in the Gornera between 10 July (192) and 29 August (242) (figure 5.7). It is difficult to compare this method of data collection with figures 5.5 and 5.6 due to how frequent the samples are collected and also the difference in sample size. However, this figure shows diurnal variation once again, similar to figures 5.5 and 5.6, and this method also shows a large decrease in suspended sediment towards the start of the time series. The gap in data on 20 July (201) was a reading of 0.0 kg/day and as the samples are collected manually, on this occasion, there must have been an error with the sample. The lowest reading was measured towards the beginning of this time series on 25 July (206) and it measured 0.21 kg/day. Suspended sediment then gradually increased after this date and peaks at 2.19 kg/day on 10 August (222). Sediment cones show a large decrease until 25 August (237) where one last fluctuation occurs towards the latter stages of the time series as a measurement of 1.77 kg/day was attained.

Figures 5.5, 5.6 and 5.7 all show similarities to a certain extent with all three methods showing diurnal variation. All three methods show a relatively steep decrease in early stages of the time series and all fluctuate at similar times at the beginning on 17 July (198), however, Manning sampler fluctuates much higher than the other two methods meaning this method could be most representative. The photoelectric method fluctuates least and seems to underestimate the values, meaning this method could be least representative. On 3 August (215), all three methods fluctuate at similar times again, and just like the beginning of these time series, Manning sampler fluctuates most, and photoelectric data fluctuates least. A pattern is now starting to occur within these data- sets, and once again, towards the latter part of these time series there is another fluctuation on 27 August (239) and Manning once again has the largest fluctuation and subsequently photoelectric has the least.

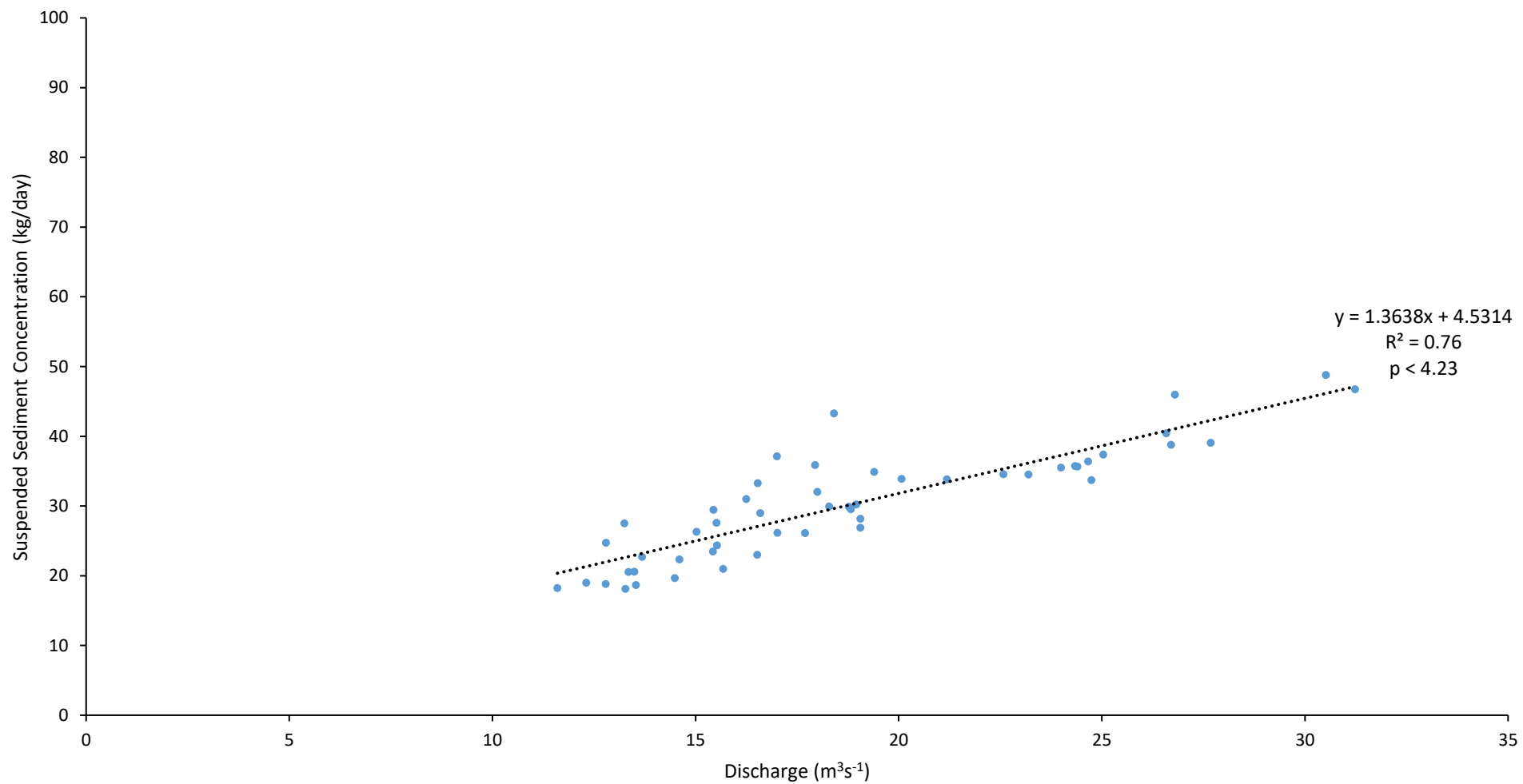


Figure 5.8: Daily totals of suspended sediment derived from a Partech photoelectric suspended sediment monitor against discharge between 10 July- 29 August 1982 (192-242) in the Gornera.

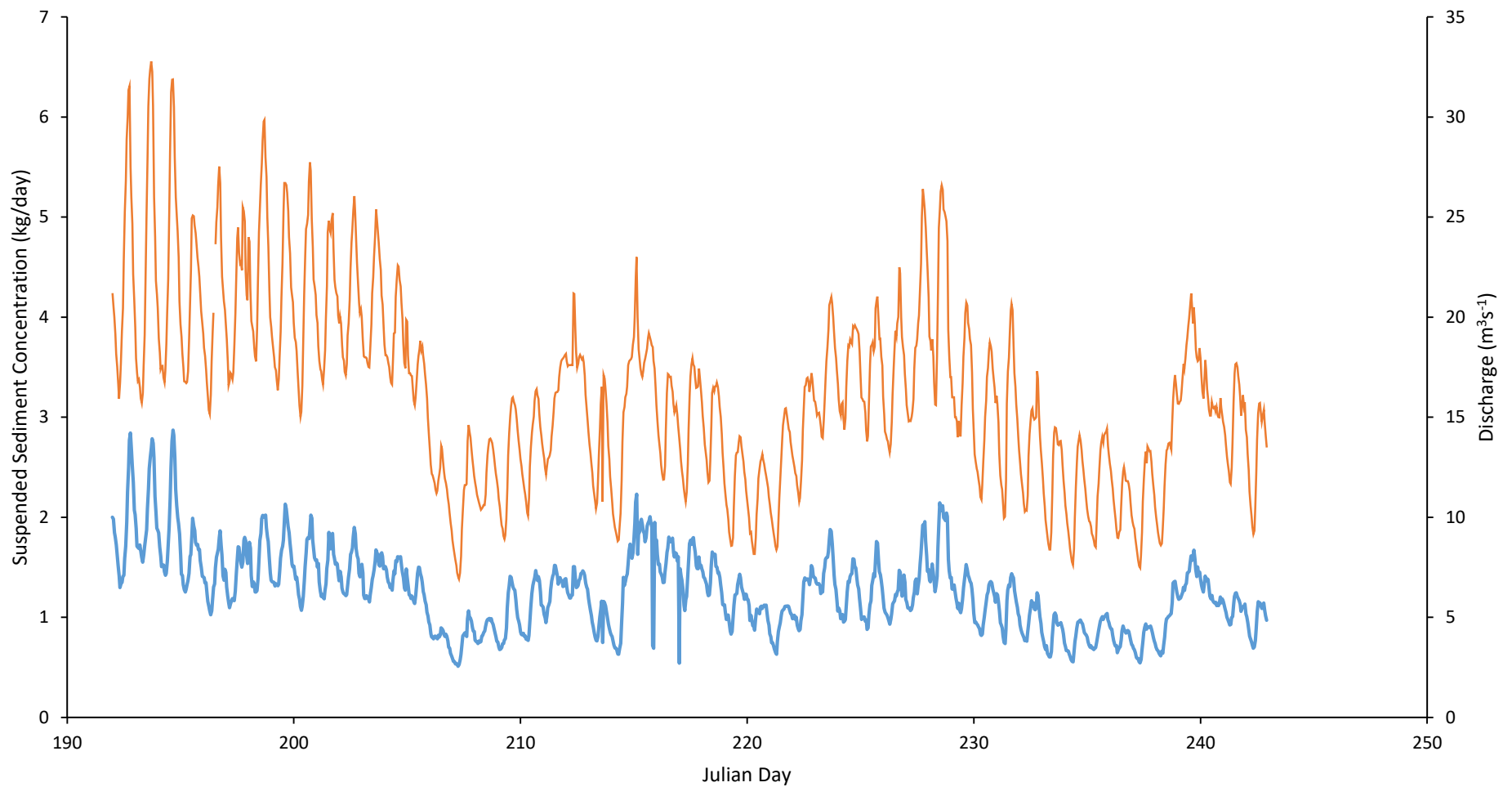


Figure 5.9: Hourly values of suspended sediment concentration derived from Partech photoelectric suspended sediment monitor (blue) and discharge (orange) between 10 July- 29 August 1982 (192-242) in the Gornera.

Daily totals of suspended sediment derived from a Partech photoelectric suspended monitor have been plotted against discharge between 10 July- 29 August (192-242) (figure 5.8). From looking at figure 5.8, it would seem that discharge has a relatively strong effect on photoelectric suspended sediment due to the R^2 being relatively high (0.76). However, as the statistical significance is also very high ($p = < 4.23$), this suggests that the association is not statistically significant, meaning that discharge and suspended sediment deriving from a Partech photoelectric suspended sediment monitor do not correlate.

Figure 5.9 is an hourly time series of photoelectric suspended sediment against discharge between 10 July- 29 August (192-242). Due to figure 5.8 having a relatively high R^2 (0.76), it was expected that both variables would follow a similar pattern. However, discharge seems to show more variation which might be why both discharge and photoelectric suspended sediment do not correlate and might also be why both variables are not statistically significant. Figure 5.9 shows the three largest measurements simultaneously for both variables at the beginning of the time series on 10, 11 and 12 July (192, 193, 194). Both variables also reach their lowest values synchronously on 26 July (207) as suspended sediment measures at 0.5 kg/day and discharge measures $6.9 \text{ m}^3\text{s}^{-1}$. There is also a large surge in both suspended sediment and discharge towards the latter stage of this time series on 27 August (239) as suspended sediment measures 1.7 kg/day and discharge measures $20.4 \text{ m}^3\text{s}^{-1}$.

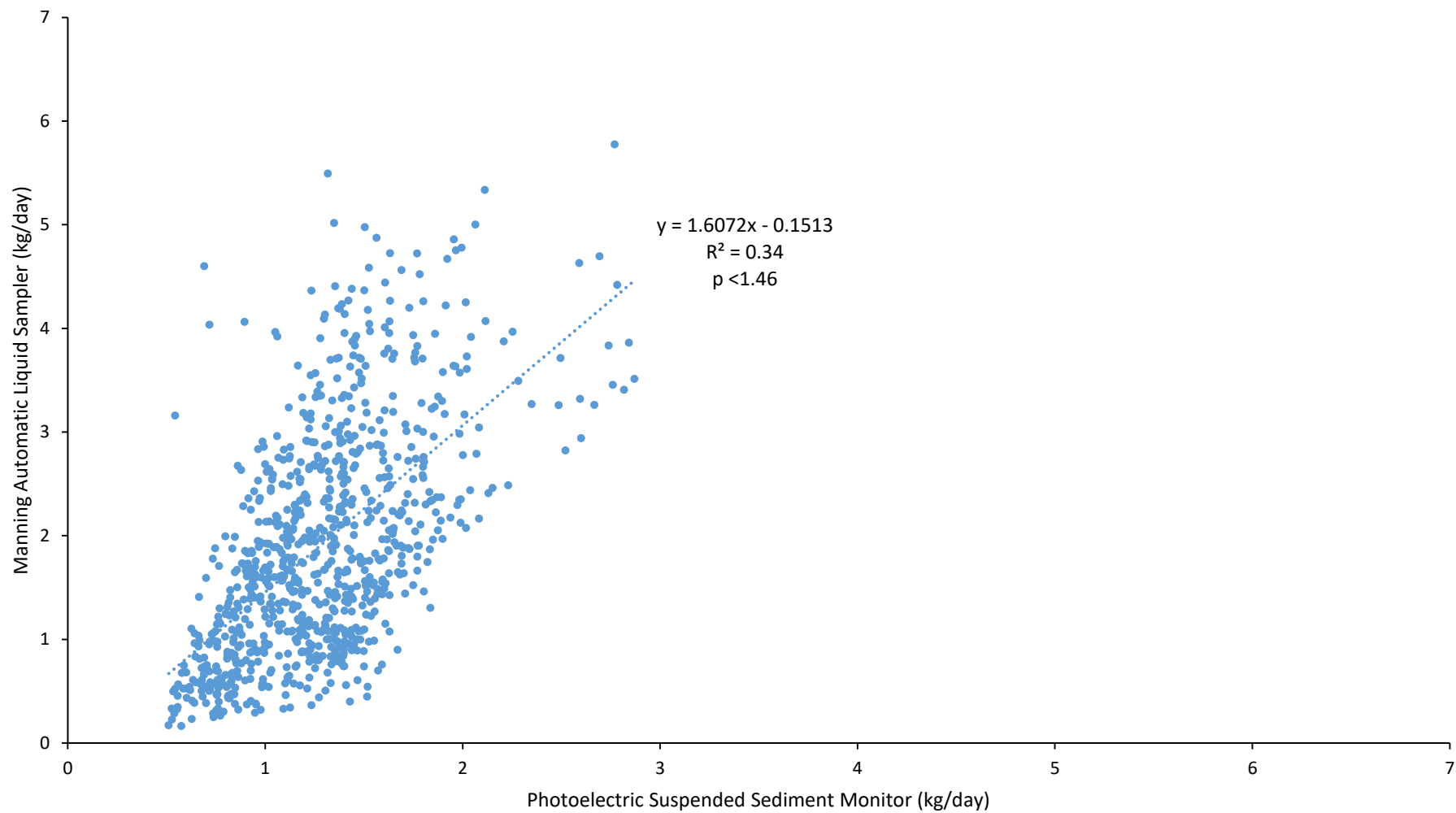


Figure 5.10: Hourly plot of suspended sediment concentration derived from a Partech photoelectric suspended sediment monitor against a Manning Automatic liquid sampler between 10 July- 29 August 1982 (190-242) in the Gornera.

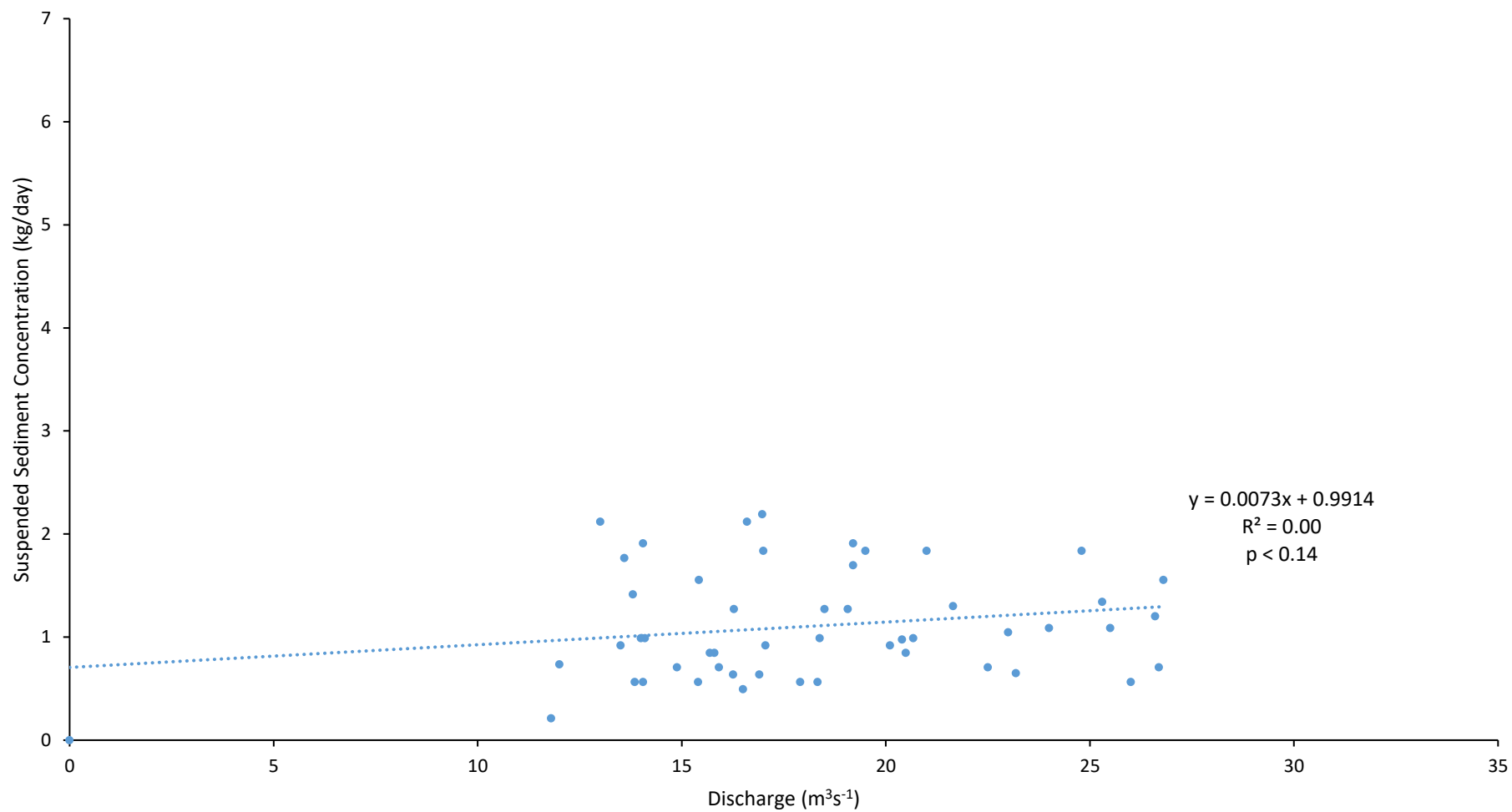


Figure 5.11: Scatter plot of daily sediment concentration derived from sediment cones against discharge between 10 July- 29 August 1982 (192-242) in the Gornera.

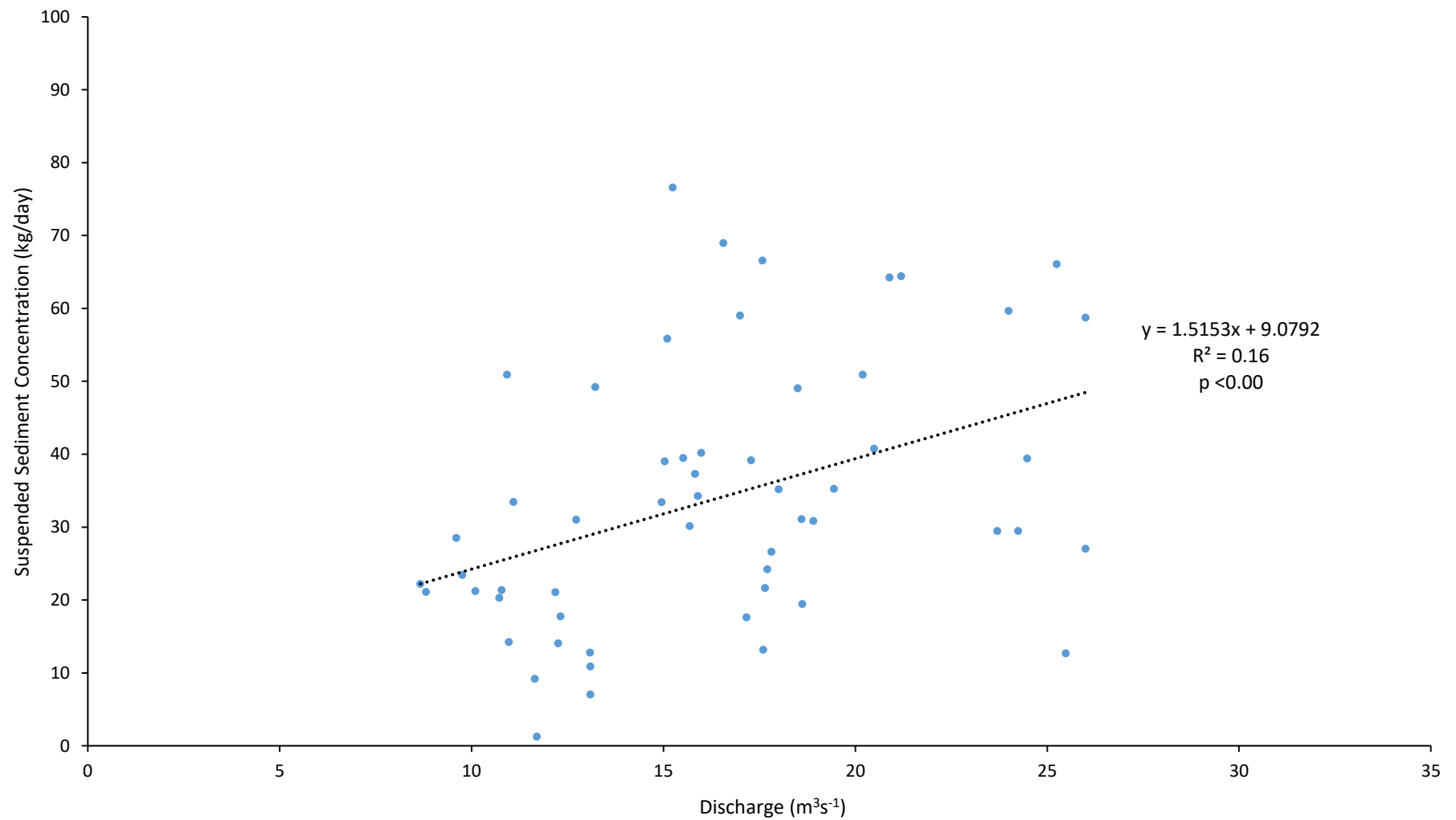


Figure 5.12: Scatter plot of daily values of sediment concentration derived from a Manning automatic liquid sampler against discharge in the Gornera between 10 July- 29 August (192-242) 1982.

A scatter plot has been created to assess how suspended sediment deriving from a Partech photoelectric suspended sediment monitor affects suspended sediment collected by a Manning automatic liquid sampler between 10 July and 29 August (192-242) (figure 5.10). With both sample size and sample frequency being similar for both methods, it was expected that the two variables would correlate strongly, however, the R^2 is relatively weak (0.34) and the p-value is relatively high ($p = < 1.46$) meaning that the association is not statistically significant and both variables do not correlate well. Reasons for a weak correlation could be due to an error in data collection, leaving gaps for the values, or it could also be data being collected at different times during the hour which would produce different results.

Figure 5.11 is a scatter plot created to assess how much of an effect discharge has on suspended sediment concentration collected by 50 L sediment cones between 10 July- 29 August (192-242). It was expected that sediment cones would have minimal effect on discharge and both variables would not correlate. This would prove to be correct as the R^2 is non-existent (0.00) and the p-value is also higher than the alpha ($p = < 0.14$) which confirms that the correlation is not statistically significant. Compared to figures 5.3 and 5.10, sediment cones have least effect on discharge compared suspended sediment collected by a Manning automatic sampler (0.23) and a photoelectric suspended sediment monitor (0.34).

There are several factors that contribute towards sediment cones having the least effect on discharge. Sample size is one reason, as sample size for sediment cones is much larger compared to both other methods of data collection. Another reason could be due to data being collected manually for a sediment cone, whereas, both other methods collect data automatically. Another reason could be frequency of data collection, as sediment cones have one sample collected per day, whilst other two methods have close-interval samples attained. These factors can help determine how representative a sample is, or even how a method could underestimate values meaning that method is limited.

Figure 5.12 is a scatter plot showing daily totals of suspended sediment collected by a Manning automatic liquid sampler against discharge between 10 July- 29 August (192-242). From looking at figure 5.12, it would seem that discharge has minimal effect on daily totals of suspended sediment due to the R^2 being very low (0.16). However, as the p-value is lower than the alpha ($p = <0.00$) it confirms that the correlation is statistically significant between the two variables but the values do not show much variation.

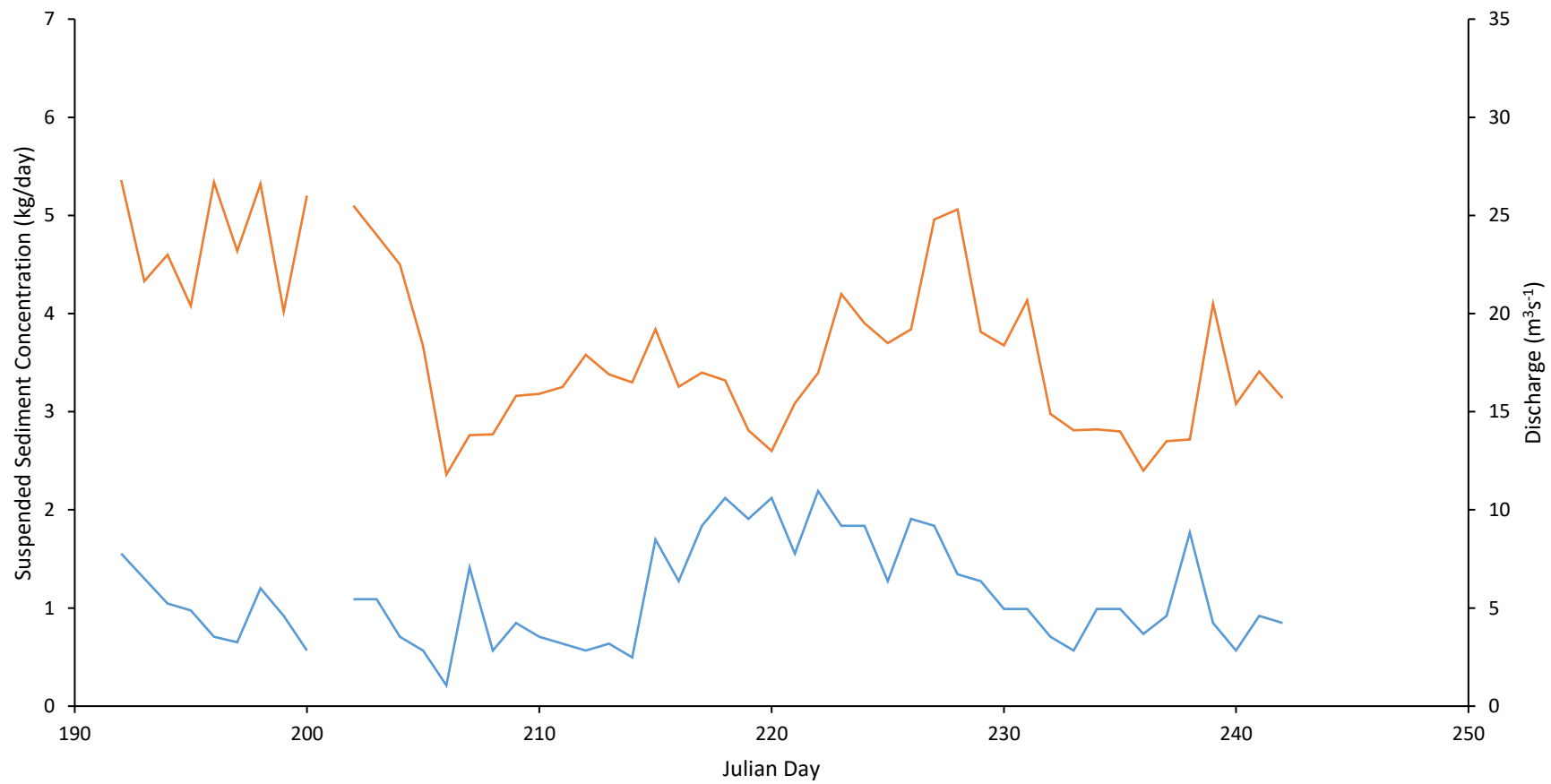


Figure 5.13: Daily values of suspended sediment derived from sediment cones (blue) against discharge (orange) from the Gornera between 10 July- 29 August 1982 (192-242).

Suspended sediment derived from once a day 50 L sediment cones plotted through time against discharge were taken between 10 July- 29 August (192-242) 1982 from the Gornera (figure 5.13). A data gap occurs in the series on 20 July (201) due to an error in data collection and both variables measured 0.00 kg/day and 0.00 m³s⁻¹. Similar to figure 5.11, sediment cones seem to have a minimal effect on discharge. On 15 July (196), both variables show opposite results as discharge shows large increase to 26.69 m³s⁻¹, whereas on the same day, sediment cones show relatively large decrease to 0.71 kg/day. Towards the latter stage on figure 5.13 (between 26- 28 August ((238- 240))), sediment cones have a very steep decrease from 1.77 to 0.57 kg/day, whilst discharge has an adverse effect and shows increase from 13.59 to 15.40 m³s⁻¹. A pattern is beginning to occur now as discharge seems to be having minimal effect on all three methods of data collection as the statistical significance for all methods does not seem to correlate and the synchronicity in figure 5.13 could be related to measurement interval.

A time series of sediment flux derived from a Manning automatic liquid sampler and discharge between 10 July- 29 August (192-242) taken from the Gornera has been created (figure 5.14). Both variables seem to move more synchronously compared to sediment cones and discharge (figure 5.13) and actually seem to show similar diurnal variation throughout most of the series, however, flux is derived as the product of discharge and correlation. Suspended sediment peaks on 10 July (192) and measured 5.77 kg/day at 18:00, during the same time, discharge also shows one of the highest values and measured 31.54 m³s⁻¹. This confirms that discharge has an effect on suspended sediment deriving from a Manning automatic liquid sampler. Compared to sediment cones and photoelectric suspended sediment monitor, discharge seems to affect the Manning method mostly up to now, however, the R² and p-value suggest that the correlation is not statistically significant.

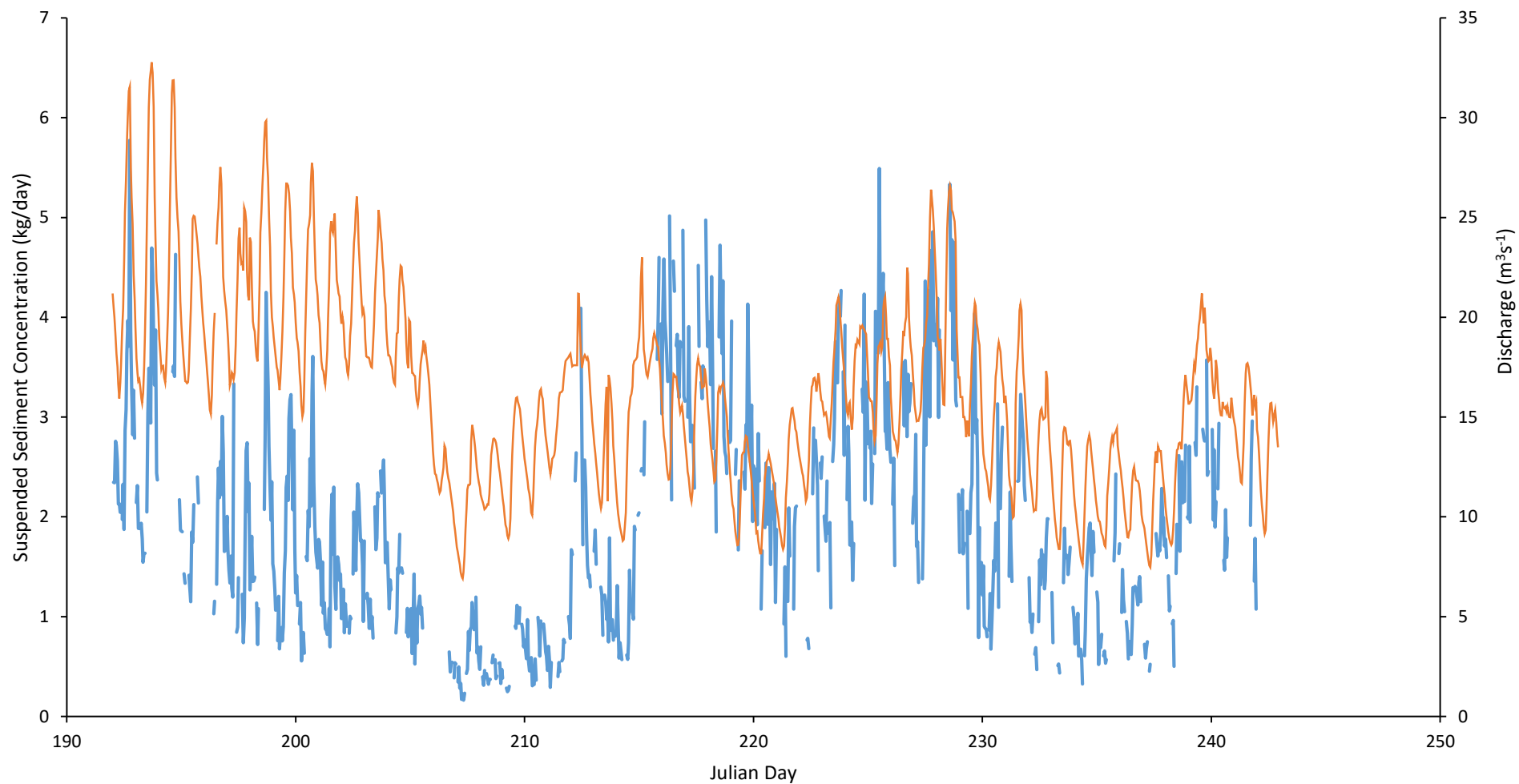


Figure 5.14: An hourly time series of suspended sediment flux derived from a Manning automatic liquid sampler (blue) and discharge (orange) from the Gornera between 10 July- 29 August (192-242).

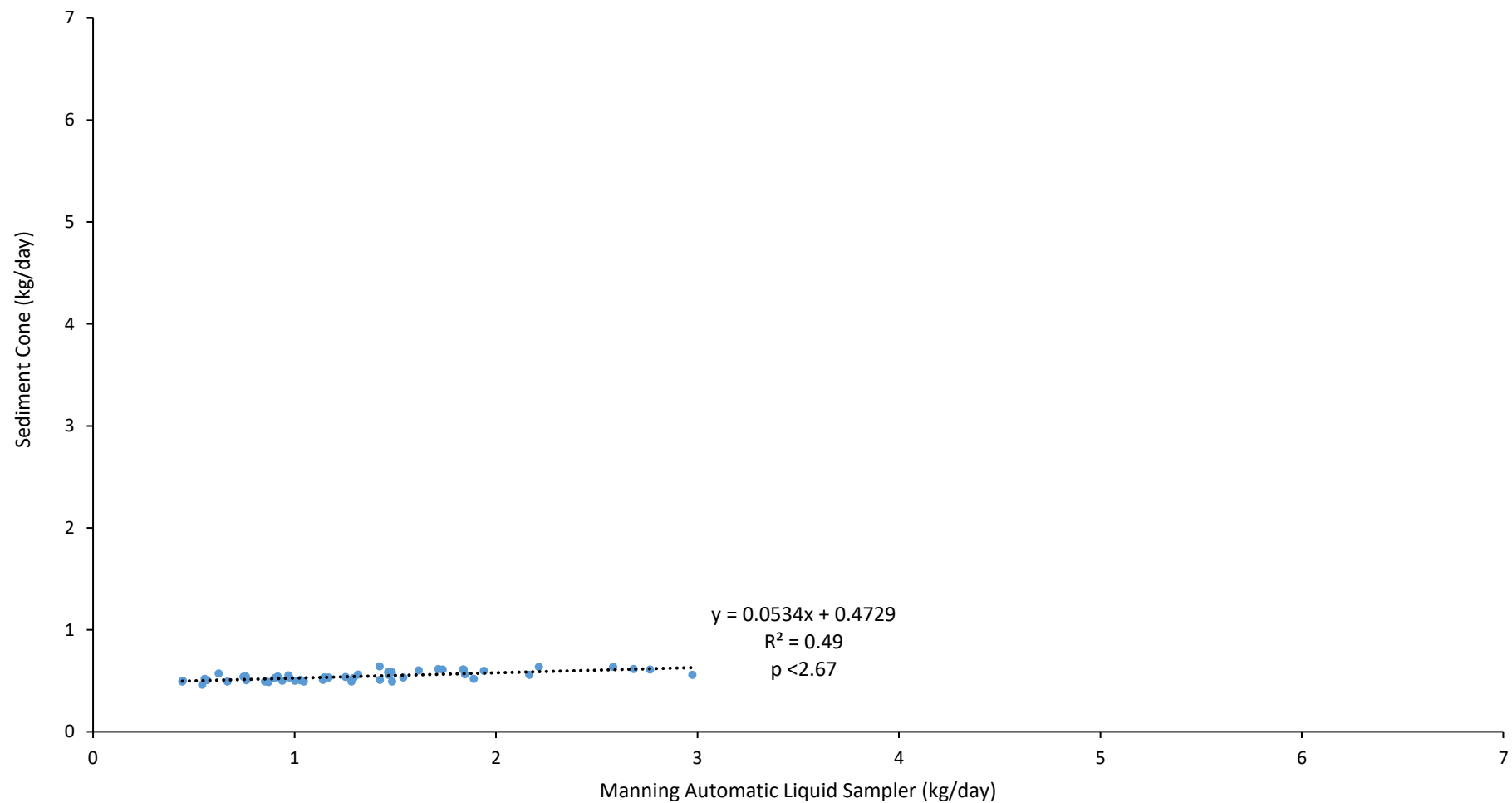


Figure 5.15: Daily scatter plot of suspended sediment concentration derived from a Manning automatic liquid sampler against sediment cones between 10 July- 29 August 1982 (192-242) in the Gornera.

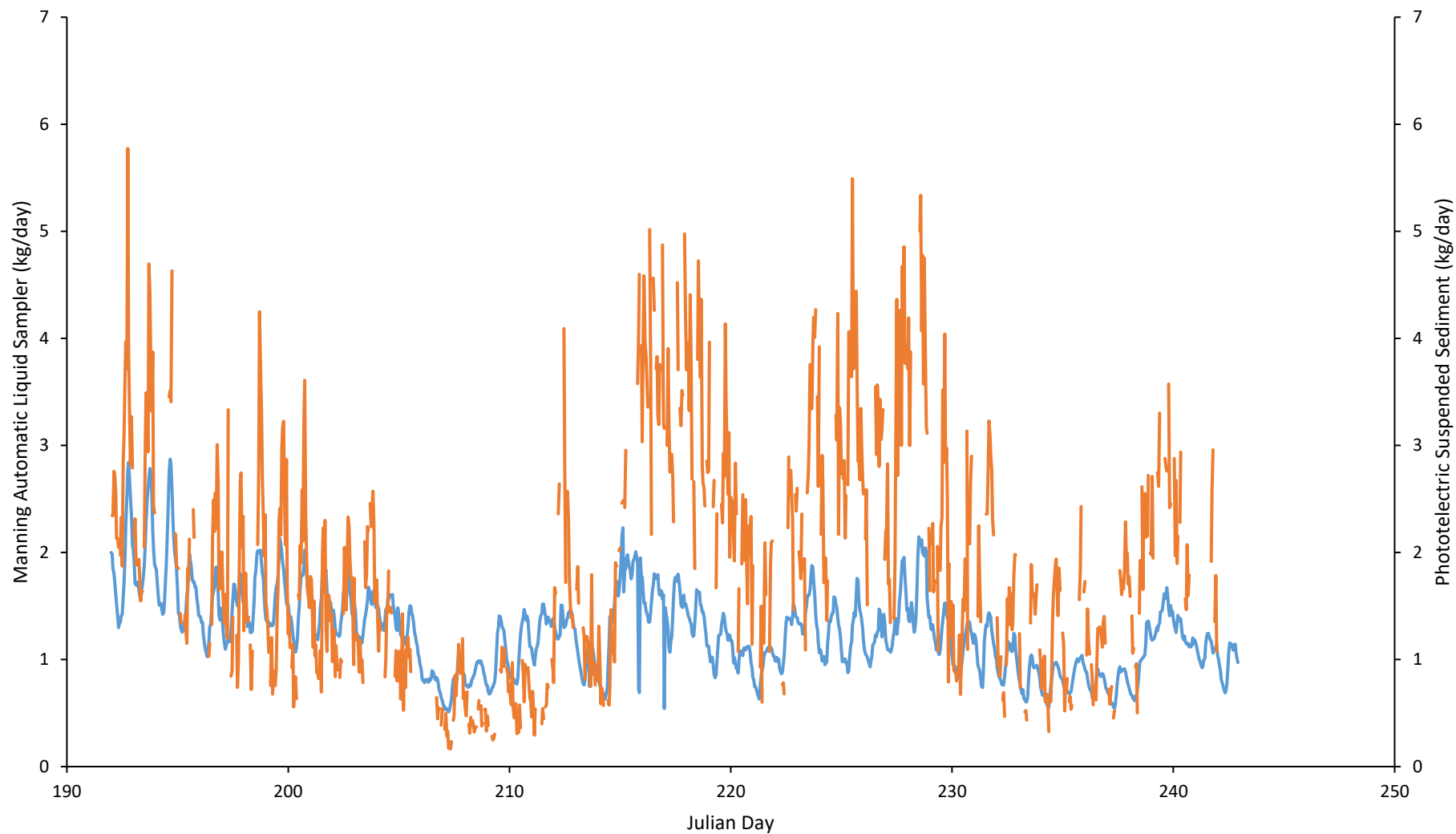


Figure 5.16: Hourly values of sediment concentration derived from the photoelectric suspended sediment monitor (blue) and sediment concentration collected by a Manning automatic liquid sampler (orange) between 10 July- 29 August (192-242) 1982 in the Gornera.

A scatter plot model has been created to see if suspended sediment collected by a Manning automatic liquid sampler has any effect on sediment cones collected in 50 L samples between 10 July- 29 August 1982 (192- 242) (figure 5.15). The R^2 between these two variables is stronger than expected, however, it is still relatively weak (0.49), and the p-value is high ($p = > 2.67$) which confirms that the correlation is not statistically significant. The R^2 between these two variables is higher than Manning automatic liquid sampler against photoelectric suspended sediment monitor on figure 5.10 (0.34). This was not expected due to similar sample size and frequency for Manning and photoelectric methods.

A time series of suspended sediment concentration deriving from a Partech photoelectric suspended sediment monitor and sediment concentration collected by a Manning automatic liquid sampler between 10 July- 29 August (192-242) is shown in figure 5.16. Both variables follow each other particularly well, however, the Manning method shows a lot more variation suggesting this method could be more representative. The difference in variation between both variables could be the reason for a weak correlation, but, another reason for a weak correlation could be errors in data collection from the Manning method. These errors cause continuous values of '0.00' to occur which had to be removed, causing data gaps. Both variables show large pulses at 18:00 on 10 July (192) as the Manning method peaks at 5.77 kg/day and photoelectric sediment monitor measures 2.8 kg/day. Photoelectric suspended sediment monitor peaks at 16:00 on 12 July (194) and Manning automatic liquid sampler also has a large fluctuation simultaneously. Both methods show their lowest measurements during the same time on 26 July (207) at 06:00, Manning method showed 0.17 kg/day and photoelectric measured at 0.50 kg/day.

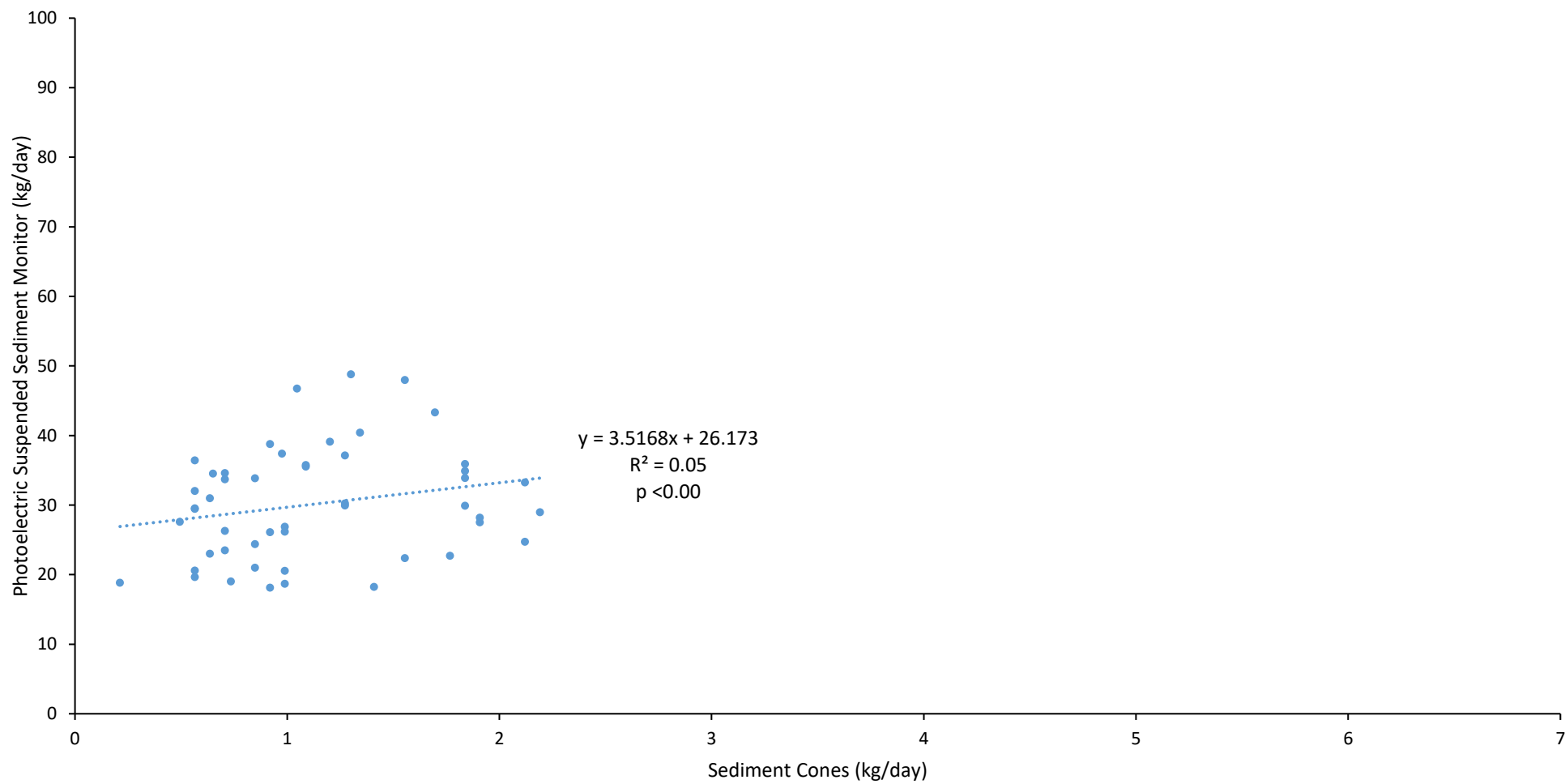


Figure 5.17: Daily scatter plot of suspended sediment concentration derived from a photoelectric suspended sediment monitor against sediment cones between 10 July- 29 August 1982 (192-242) in the Gornera.

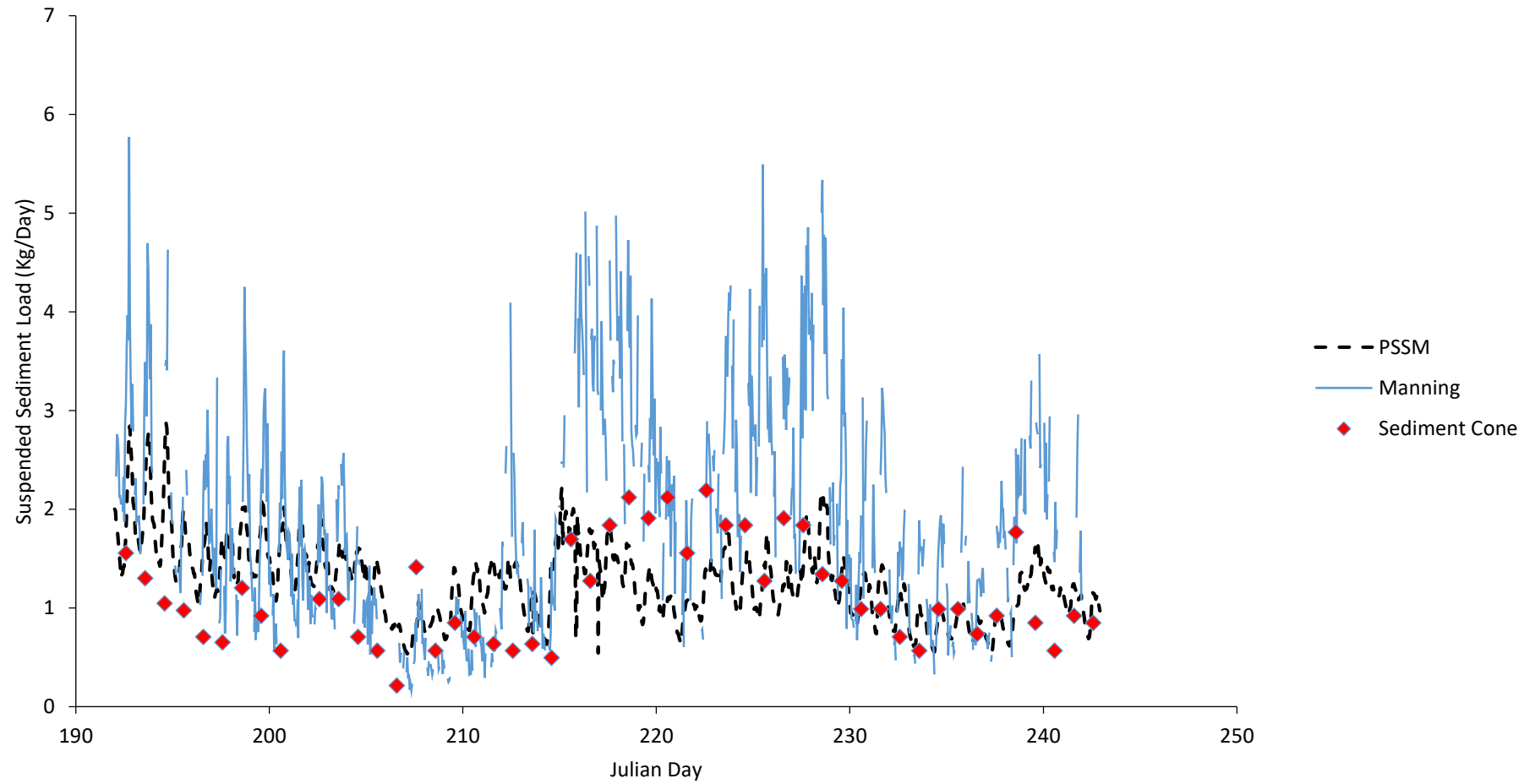


Figure 5.18: Temporal variation of sediment concentration in the Gornera: hourly values of sediment concentration turbidity derived from a photoelectric suspended sediment monitor, hourly values collected by a Manning automatic liquid sampler, and one-a-day value of sediment content from sediment cones between 10 July and 29 August 1982 (192-242).

Daily totals of suspended sediment collected by photoelectric suspended sediment monitor and sediment cones were plotted against each other between 10 July and 29 August 1982 (figure 5.17). Similar to figure 5.12, the R^2 is almost non-existent (0.05) and the p-value is also lower than the alpha ($p = <0.00$) which means that the correlation is statistically significant and variables correlate rather well. The reason for a low R^2 could be due to both variables producing different sample sizes, and also a difference in sample frequency as sediment cones have a much larger sample size, whilst photoelectric data is recorded close-interval and sediment cones produce one sample per day. The R^2 between these two variables is the lowest compared to Manning against photoelectric which recorded an R^2 of 0.34 (figure 5.10), and Manning against sediment cones which recorded an R^2 of 0.49 (figure 5.15).

Figure 5.18 shows temporal variation for photoelectric suspended sediment monitor, Manning automatic liquid sampler and sediment cones taken from the Gornera between 10 July and 29 August 1982 (192-242). The Manning method seems to be most suitable as it shows most variation compared to photoelectric and sediment cones, which means it is more representative to the actual study, whereas both other methods seem to underestimate the values compared to the Manning method. Photoelectric and sediment cones do seem to show a similar pattern but with less variation as the values seem to be limited compared to the Manning method. It does not seem possible to use photoelectric or sediment cones to suggest actual values due to the Manning method being more variable. According to figure 5.18, Manning method seems to be most suitable to use compared to other two methods. Due to sediment cones only producing one result per day, it seemed clearer to present the results in figure 5.18 in scatter form, and results do seem to follow a similar pattern to the photoelectric data, however, as photoelectric data records data continuously, it seems that results are more variable than sediment cones.

5.1. Summary of Results

Suspended sediment concentration deriving from all three methods (sediment cones, Partech 740 photoelectric suspended sediment monitor, and Manning automatic liquid sampler) were plotted against discharge (figures 5.8, 5.11 and 5.12). Both photoelectric and sediment cone methods did not seem to correlate with discharge (figures 5.8 and 5.11) due to the R^2 being relatively low or non-existent and the p-value being higher than the alpha (0.05) meaning the correlation is not statistically significant. However, the Manning method did seem to correlate well with discharge (figure 5.12) as the R^2 was almost non-existent and the p-value was also low, meaning the correlation is statistically significant but the values did not show much variation.

All three methods of data collection did produce similar results during certain time periods, as they all show large fluctuations towards the beginning of the time series (figures 5.2, 5.4 and 5.7), however, the Manning method seems to show more variation within results which helps to prove that this method of data collection seems to be more representative to the study. Both sediment cones and photoelectric methods seem to underestimate the values compared to the Manning method as they showed less variation. Suspended sediment peaks on 10 August (192) for the Manning and photoelectric data, however, it does not peak until 6 August (218) when measured with sediment cones. Once again, Manning and photoelectric methods both show their lowest readings on 26 July (207) with Manning recording 0.17 kg/day and photoelectric recording 0.50 kg/day, however, sediment cones produce their lowest reading on the next day as they measure 0.56 kg/day. Results for sediment cones are likely to differ from Manning and photoelectric due to sample size and sample frequency.

Discharge is the main driver of suspended sediment as it helps transport sediment downstream through river channels, especially during the ablation season when discharge rates peak. However, suspended sediment concentrations will be low during this period of high discharge which means suspended sediment concentrations should be at their highest levels during the accumulation period when discharge is much lower. This is not always the

case as warm winter periods means snow/ice will fall in liquid form as precipitation meaning concentrations will be much lower due to higher discharge periods. Gaps appear within figures 5.2, 5.7, 5.13, 5.14, 5.16 and 5.18 which is mainly due to the Manning automatic liquid sampler producing errors within the results, and these have been removed to help validate the study. As data has been recorded automatically for the Manning and photoelectric methods, it is difficult to acquire a full set of perfect results which means data gaps will almost certainly appear within results collected by these two methods. However, there was also a gap within the sediment cone data on 20 July (201) which is an anomaly because data for this method is collected manually. Data cleaning is extremely important within data analysis as it tidies up the data and also removes the values which show a false reading, enabling data gaps to occur.

6. Discussion

Although the intention was to use long homogenous series, the available data are limited in many aspects. Ideally, records would be uninterrupted but as data records automatically for two of the three methods of data collection, various problems have occurred such as large pieces of sediment being lodged in the equipment forcing errors in data collection. However, these errors have been extracted, leaving empty values within results to make the time series as homogenous as possible. There are large variations in terms of comparing methods of collecting suspended sediment concentration and also when comparing these differing methods with discharge results. As sediment cones only take one 50 L recording a day, it is difficult to compare these results with those collected in close-interval time periods, meaning daily totals were calculated for Manning and photoelectric methods so a direct comparison could be made for all three variables.

As data has been attained from 1982, only three methods of data collection have been identified, however, there are now new and improved methods for collecting suspended sediment concentration for example, Isokinetic samplers which are similar to sediment cones as they collect samples manually.

A matrix table has been created to compare which sampling techniques are statistically significant (Table 2.0). The photoelectric and sediment cone methods do seem to correlate as the R^2 is almost non-existent (0.05) and p-value is also non-existent ($p = <0.00$) meaning the correlation is statistically significant, however, the values do not seem to show much variation. The two variables were not expected to correlate due to both sample size, and sample frequency being different and this was proved wrong. The correlation for photoelectric and Manning methods was expected to be much stronger than the correlation for photoelectric and sediment cones due to similar sample size and frequency. This has proven to be incorrect, as the R^2 was much weaker than expected (0.34) and the p-value was much higher than the alpha ($p = <1.46$) meaning the correlation is not statistically significant between these two variables. This could be due to the numerous data gaps that

appear within the Manning data or could also be due to data being collected at different times of the day, causing the R^2 to be much weaker than expected. Sediment cones and Manning methods were not expected to correlate due to differences with sample size and frequency, this was proven to be correct as the R^2 was relatively weak (0.49) and the p-value was higher than the alpha ($p = <2.67$), meaning the correlation is not statistically significant between the two variables.

Table 2.0: Matrix of R^2 (above) and p-values (below) for daily totals of suspended sediment concentration deriving from a Partech photoelectric suspended sediment monitor, Manning automatic liquid sampler and 50 L sediment cones from the Gornera.

	Photoelectric Suspended Sediment Monitor	Sediment Cone	Manning Automatic Liquid Sampler
Sediment Cone	0.05 $P = <0.00$		
Manning Automatic Liquid Sampler	0.34 $P = <1.46$	0.49 $P = <2.67$	

Table 3.0 clearly shows that discharge has no effect on suspended sediment deriving from sediment cones as the R^2 is non-existent (0.00) and the p-value is also higher than the alpha ($p = <0.14$) which means the correlation is not statistically significant. The photoelectric method also does not correlate with discharge because although the R^2 is much stronger (0.76), the p-value is also higher than the alpha ($p = <4.23$) meaning the correlation is not statistically significant and the correlation is in fact weak. The Manning method however, does seem to correlate with discharge because even though the R^2 is very weak (0.16), the p-value is also lower than the alpha ($p = <0.00$), meaning the correlation is statistically significant, but, the values do not show much variation.

The data shows that although discharge is a driver of suspended sediment concentration, correlations can be useful between suspended sediment concentration and discharge only over short, twenty- four hour periods as suggested by Collins (1979). Fluctuations in suspended sediment concentration are normally associated with discharge fluctuations (Stott & Grove, 2001) however, in this study it is only the case for one of three variables (Manning). The large volume of sample collected by sediment cones might suggest that they collect the most representative sample of suspended sediment however, the Manning automatic liquid sampler and Partech photoelectric suspended sediment monitor collect more frequent samples so they are more representative temporally.

Stott and Grove (2001) believe that fluctuations in suspended sediment concentrations are normally associated with discharge fluctuations, and the relationship between discharge and suspended sediment concentration increases for rainfall-induced events, but no similar relationship could be established for non-rainfall-induced events. This has proven to be correct for two methods of data collection, however, for the Manning method, a relationship was established as both variables correlated well, but there was limited variation. The statement by (Legatt *et al.*, 2015) where he believes sediment transport is determined by interaction between daily and seasonal patterns of meltwater discharge and amount of sediment available has proven to be valid, as discharge is a driver of sediment transport, and discharge is also the reason for short and long-term variations in suspended sediment concentrations.

Table 2.0: Matrix of R^2 (above) and p-values (below) for daily totals of suspended sediment concentration deriving from a Partech photoelectric suspended sediment monitor, Manning automatic liquid sampler and 50 L sediment cones against discharge from the Gorrera.

	Discharge
Photoelectric Suspended Sediment Monitor	0.76 P= <4.23
Sediment Cone	0.00 P= <0.14
Manning Automatic Liquid Sampler	0.16 P= <0.00

6.1. Discharge

Discharge draining from the Gornera is the main controlling factor towards sediment transport and this arises from snow- and ice-melt and liquid precipitation. The total mass of suspended sediment transported downstream determines how high or low sediment concentration is and the volume of water discharged. To predict the sediment load of a glacially formed river, we need to understand the interaction of numerous factors, including climate, precipitation (both average and peak), discharge (volume and velocity), basin geology, human impact, and the size of the drainage basin. Generally, the higher the discharge, the higher volume of sediment carried (Milliman & Syvitski, 1992). In the ablation season of 1982, discharge (figure 5.1) in general was larger than the norm as it was the first of many very warm summers of the late twentieth century (figure 4.1), meaning increases in suspended sediment transport, but subsequently, sediment concentrations were relatively low as a result of high discharge. Table 3.0 shows that out of the three methods of data collection, only one correlates with discharge which was the Manning method.

Discharge measurements on the Gornera river are recorded automatically at hourly intervals on the half hour by Grande Dixence. In periods of high discharge, the gauging station has to be degravelled, removing large boulders and also to stop gravel beds forming at the station's base. A large gate at the base of the structure opens which allows water to flow through a flume at high velocity, removing any build-up of bedload. Degravelling occurs twice a day, once between 05:30 and 06:30 and secondly later on in the day at ~20:30. Degravelling can have an effect on data collection as it can cause false readings during its release, meaning data gaps will occur. The gauging station located at the Gornera river flow into a single channel and measurements are only taken during the ablation season (May- October). Discharge in winter months is minimal and is mainly made up of groundwater.

Discharge is at its highest period between 10- 24 July (192- 205) and actually peaks on 11 July at $32.7 \text{ m}^3\text{s}^{-1}$ (figure 5.1). During this time, subsequently, suspended sediment concentrations collected by a photoelectric suspended sediment monitor (figure 5.9) and Manning automatic liquid sampler (figure 5.14) also peak during this period, but sediment cones are relatively steady during this period (5.13).

6.2. Photoelectric Suspended Sediment

Suspended sediment concentration has been collected using a Partech 740 photoelectric suspended sediment monitor in the ablation season of 1982 for the Gornera. This method of data collection is recorded automatically during close-interval periods by a 2 ml monitor with results showing various interesting values between 10 July and 29 August (192- 242).

Between 10- 13 July (192- 195), three large fluctuations in suspended sediment concentration occur, and during this period, suspended sediment peaks at 5.77 kg/day (figure 5.4). Simultaneously, discharge rates also peak at $32.7 \text{ m}^3\text{s}^{-1}$ (figure 5.1), however, this method of data collection does not correlate with discharge, because even though the R^2 is relatively strong (0.76), the p-value is much higher than the alpha ($p = <4.23$), meaning the correlation is not statistically significant. Both variables also reach their lowest values synchronously on 26 July (207) as suspended sediment measures 0.5 kg/day and discharge measures $6.9 \text{ m}^3\text{s}^{-1}$ which is surprising as both variables do not correlate.

Because photoelectric data is recorded in ml, daily totals had to be calculated, and converted into kg/day units so a direct comparison could be made with both other methods. A scatter plot was created so photoelectric data could be directly compared against sediment cone data (figure 5.17). The result was surprising, because even though both variables have different sample size and sample frequency, they both correlate well as the R^2 was almost non-existent (0.05), but, the p-value was also lower than the alpha (0.00) which means the correlation is statistically significant.

Suspended sediment concentration deriving from a Manning automatic liquid sampler has also been compared against photoelectric suspended sediment data, and the result attained was not expected, because both methods do not correlate even though sample size and sample frequency is very similar. The R^2 was lower than expected (0.34) but the p-value was much higher than the alpha (1.46) meaning the correlation is not statistically significant. Reasons for a low R^2 could be due to data gaps within the Manning data.

Suspended sediment collected by a Partech 740 photoelectric suspended sediment monitor seems to be a suitable method of data collection, as the 2 ml monitor collects data automatically, meaning human interference is not necessary until data is calibrated. Also, as shown on figure 5.18, the photoelectric data does show a good range of diurnal variation throughout the time series, meaning this method would be representative to the study and the values have not been largely underestimated. However, one improvement the photoelectric suspended sediment monitor would need to be a more representative method is if the same size was larger,

6.3. Manning Automatic Liquid Sampler

Suspended sediment concentration has been collected during the ablation season of 1982 for the Gornera by a Manning automatic liquid sampler. This method of data collection is the original method, meaning data from both other variables had to be converted into kg/day for a direct comparison. Similar to photoelectric suspended sediment data, Manning automatic liquid sampler collected data during close-interval periods between 10 July- 29 August (192- 242) (figure 5.2) and sample size is relatively small (200 ml) compared to 50 L sediment cones.

A scatter plot has been created to see if the Manning method correlates with the sediment cone method (figure 5.15), and results were as expected because due to differences in sample size and frequency, both variables do not correlate. The R^2 was actually higher than expected (0.49), however, the p-value is much higher than the alpha ($p = < 2.67$), meaning the correlation is not statistically significant. The Manning and photoelectric methods showed some similarities, because there are three large surges in sediment towards the beginning of both time series between 10- 13 July (192- 195). Both sample size and frequency are similar as well, so it was predicted that the correlation between these two variables would be relatively strong. However, this was not the case, because the R^2 for both methods was not as strong as expected (0.34) this may be due to numerous gaps within the Manning method causing the R^2 to drop significantly. The p-value was also a lot higher than the alpha as well ($p = < 1.46$) meaning the correlation between both variables was not statistically significant.

Data collected by a Manning automatic liquid pump sampler was plotted against discharge (figure 5.12) and both variables were not expected to correlate. However, this was not the case, because the R^2 is almost non-existent (0.16) and the p-value was also non-existent ($p = < 0.00$), it means the correlation is statistically significant, but there is minimal variation. The Manning method is the only method which positively correlates with discharge, meaning this method could be most representative. Also, on figure 5.18, the Manning method shows

most diurnal variation compared to both other methods, and does not underestimate the values.

Manning automatic liquid sampler is a useful method of data collection as data is recorded during close-interval periods automatically, similar to the Partech 740 photoelectric suspended sediment monitor, because no human intervention is needed until data is calibrated. One disadvantage of using the Manning method is that sample size is relatively small compared to sediment cones, but samples are taken more frequently. If the Manning automatic liquid sampler sample size was larger, this would be an ideal sample and would also be more representative because this method does not underestimate values like both other methods.

6.4. Sediment Cones

Sediment concentration data has been collected once a day by 50 L sediment cones in the Gornera for the ablation season of 1982. As water filters through the bottom of a cone, remaining sediment is collected and then calculated. Between 10 July- 29 August, samples of suspended sediment were taken and these were directly measured against discharge (figure 5.13). Suspended sediment concentration deriving by sediment cones seems to have the weakest correlation with discharge out of all three methods as the R^2 is non-existent (0.00) and the p-value is also higher than the alpha ($p = <0.14$) meaning the correlation is not statistically significant (figure 5.11). Reasons for such a weak correlation could be due to the large sample size of the sediment cone, or maybe due to only one sample a day being taken per day, it could possibly weaken the R^2 .

Sediment cones differ to both other methods as the photoelectric and Manning methods both have three large pulses in suspended sediment towards the beginning of study period between 10- 13 July (192- 195), whilst sediment cones actually show a decline in suspended sediment during this time (figure 5.18). This could be due to sediment cones showing least variation out of the three methods, whilst the Manning method shows most variation. The sediment cone seems to mostly underestimate the values and they also seem to be very limited compared to both other methods, meaning the sediment cones could be least representative. The most surprising factor from the sediment cone data is how it positively correlates with the photoelectric data; however, the correlation does not show much variation. This was not expected due to differences within sample size and frequency between the two variables.

Sediment cones are a suitable method of collecting suspended sediment concentrations as they have a very large sample size compared to both other methods, however, as only one sample a day is taken, it is difficult to determine whether the method is a representative sample or not. One other characteristic of sediment cones is that data has to be collected manually rather than being collected automatically like both other methods so sediment

cones are more labour intensive, however, less errors will occur within data due to personnel being available to amend the error, meaning no data gaps should be found within the results.

7. Conclusion

Snow and ice melt provide large amounts of downstream river flow with varying proportions in proglacial streams, which can determine how much sediment is transported. The form of the suspended sediment concentration/discharge relationship for a drainage basin reflects the overall pattern of erosion and sediment delivery operating in the upstream area (Walling & Webb, 1982). During data analysis of suspended sediment concentration and discharge from the Gornera, Swiss Alps for the ablation season of 1982, it became clear that only one method of data collection correlated with discharge and that was the Manning method. Even though the R^2 was almost non-existent (0.16), the p-value was lower than the alpha ($p = <0.00$) meaning this was the only method to positively correlate with discharge. The photoelectric method seems to correlate least with discharge because even though the R^2 was relatively strong (0.76), the p-value was the highest out of all three methods ($p = <4.23$) meaning this method was not statistically significant.

Results from all three methods were attained using different units so it became pivotal to this study that data was calibrated into the same units (kg/day) so a direct comparison could be made. Once results were calibrated, it became clear that the Manning method would be most suitable to use for this study. Not only is this the original method of data collection, but it also shows most variation out of all three methods in figure 5.18, as the photoelectric and sediment cone data seem to underestimate the values and results seem to be limited compared to the Manning method, meaning it would be most representative to use. The sediment cone data seemed to show least variation out of the methods used, maybe this was because of the limitation of sample frequency compared to the close-interval samples, meaning this method would be least representative. The photoelectric data did show a good range of diurnal variation, however, compared to the Manning method, some of the values were limited, meaning this method was not as representative as the Manning method.

After comparing all three methods of data collection, it is clear to see what an ideal sample would be. As sediment cones collect data in much larger samples (50 L) compared to both other methods, it would seem that this method would be most representative for this study, however, due to the limitation within data collection compared to the close-interval methods, this is not the case. The ideal sample would be one similar to the Manning method, but with a larger sample size, making the sample more representative. The Manning automatic liquid sampler is the original way in which suspended sediment concentration is measured in melt water streams and rivers and many believe this method to be most reliable.

Photoelectric suspended sediment monitor data originally records the colour of water and actually has no meaning until this data is calibrated into the same units as Manning data, and this once again proves that Manning method is fundamental in this study. Once data was calibrated, a relationship is used to reconstruct suspended sediment concentration from turbidity data which is recorded continuously. The main disadvantage with the photoelectric suspended sediment monitor is that it relies on strength of the relationship which is traditionally poor in Alpine rivers where high energy means suspended sediment size is highly variable, however, the advantage of using this method is effort and time saved due to data being collected automatically.

As sediment cones only take one recording per day, it is difficult to determine if this is a representative sample as suspended sediment transport is constant, however, a Partech 740 suspended sediment monitor and Manning automatic liquid sampler records data during close-interval periods which is a better represented sample for this study. One other important factor which affects recordings of suspended sediment is if a method collects data automatically or manually. As sediment cones collect data manually, samples will always be taken as human intervention is available, however, both other methods record data automatically and if errors occur in data collection, it is only noticeable once data gets calibrated, meaning data gaps will occur. Weather and climate conditions are controlling factors of this study as warm weather means more ice- melt, and increases discharge.

However, colder conditions would generally mean less ice-melt, causing discharge to decrease unless heavy precipitation occurs.

The Grande Dixence hydroelectric power station also plays a large role in measurements taken in this area as the dam releases large volumes of discharge twice a day into the Gornera causing suspended sediment transport to increase. This is the reason why sudden surges occur within several models. Numerous challenges and setbacks occurred during periods of data collection making data analysis a challenge at times. One main challenge was data beginning and ending during different time periods which had to be calibrated in order for a direct comparison to be made. One further challenge was some methods of data collection record hourly whilst others record daily, meaning daily totals of suspended sediment and discharge had to be created in order to create flux models. The biggest setback of this study was calibrating data so that all three methods could be compared using the same units.

This study has helped prove that all three methods of data collection are suitable in terms of collecting suspended sediment in meltwater streams, however, each method contains certain weaknesses, and an ideal method would include elements from each method. This study has also helped to determine strength of correlations between suspended sediment and discharge which has proven to be minimal for the photoelectric and sediment cone methods, but positive for the Manning method. It has been suggested for future reference that a new study would be set up to investigate further into new methods of collecting suspended sediment concentration which can be compared to ones used for this study. It would have to be set up during the ablation season where discharge rates are at their peak. There is a lack of research that compares suspended sediment with discharge so it would be good to investigate further into this field to get a better idea of which data collection method would be best suited.

8. References

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